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METHODS OF PROCESSING SATELLITE DATA

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INTRODUCTION

The data-processing requirements for space related data have increased by orders of magnitude during the past six years. Prior to the advent of the satellite, this problem was characterized by the processing of data from a sounding rocket where a successful flight would produce approximately 5,000 data points per second for 600 seconds; thus 3,000,000 data points would have to be processed per flight and these flights were relatively infrequent. In contrast, the Goddard Space Flight Center's world-wide network of data acquisition stations presently receives and records data from some twenty-six satellites, performing both national and international scientific missions, with an accumulation rate of 100 hours of data per day. The 14 satellites for which Goddard has complete mission responsibility produce data at the average rate of 60 million data points per day, where a data point is defined as a single complete reading taken from a sensor. In the near future, it is anticipated that this will grow to greater than 200 million points per day.

Figure 1 gives some feeling for the magnitude of this task. On the left is shown a stack of magnetic tape reels required to record the 100 hours of data per day. On the right, is the stack of computer printout paper which would be required to present the resulting data in decoded and digitized form to the experimenter.

The anticipated trend during the coming years is shown on Figure 2. You will note that the increased data rate anticipated is not due to any marked increase in the number of satellites that will be producing data. The growth is due primarily to the progressively broader transmission bandwidths that will be used and the associated increase in data rates per satellite. For instance, an Explorer satellite typical of the 1962/63 era was capable of transmission of 50 data points a second; an Orbiting Geophysical Observatory (OGO) more typical of the 1965/70 period has a capability of 7,000 data points per second.

Furthermore, our experience with OGO during almost a year of operation is that the more data capacity one makes available to an experimenter, the more he wants. The problem of budgeting the OGO data channels between the 20 experimenters on board this satellite is an imposing one.

Such volumes of data provide the potential of an "information explosion" to the space experimenter. The realization of this potential has required significant technological advances in methods of handling the huge mass of data that is being produced by satellites. It will be the purpose of this paper to describe our present status and to indicate the areas in which further improvements must be made.

COMPONENTS OF A SATELLITE "DATA SYSTEM"

The words "data system" and its "acquisition," "processing," "reduction" and "analysis" subsystems mean many things to many men. It will, therefore, be useful to define such a system in the terminology that is used in this paper.

Figure 3 shows the various components of the "data system" and their interrelation. Although these various subsystems are located in many places as implied by the figure, they in fact form a closely integrated system in which the characteristics of any one component strongly influence the other parts of the system.

The system starts with the experimenter and his concept of the experiment that he wants to conduct on the satellite. This must be translated into equipment on board the satellite; the experimental sensor along with the onboard data encoder, data storage and telemetry equipment become key components that influence the design of the rest of the data system. For instance, the extent to which data compaction or onboard processing techniques are used is the key factor in establishing not only the amount of data to be handled but also the processing requirements on the ground. In a satellite such as the Orbiting Geophysical Observatory which handles a great variety of data, for which real-time data handling is not of primary importance, and on which the type of data processing desired by the experimenter is not readily identifiable in advance and thus cannot be built into the satellite, the major data processing burden will be transferred to the ground systems. On the other hand, certain ground requirements such as one encounters in operational satellites may dictate the design of an onboard data processing system. For instance on the Tiros Operational Satellite, which will go into operation in the coming year, the playback of the data from the Automatic Picture Taking (APT) camera has been slowed down so that conventional facsimile equipment could be used for real-time readout at the many local ground stations planned for this satellite. Another example is the on-board gridding of the pictures being planned for the Nimbus satellite; this will simplify the ground processing considerably at remote stations.

There also may be a reason for resorting to data processing techniques on board the satellite to fit the amount of data transmitted into a very limited band-width. This in turn cuts down on the amount of data that has to be processed on the ground. This band-width limitation is more typical of space probes than it is of earth-satellite systems, which are the subject of this paper. This difference is highlighted by a comparison of data rates from the Mariner IV Mars probe and the Nimbus class earth satellite data systems which transmit comparable TV pictures. On the Mariner IV the data rate at Mars distance was 8-1/3 bits per second; at this rate it took about eight hours to transmit a 200 line TV picture containing 40,000 picture elements. On the Nimbus, three 800 line pictures, representing a total of almost two million picture elements, were transmitted simultaneously in 6-1/2 seconds at an equivalent bit rate of 1,500,000 bits per second. The difference that this implies in the ground data handling is obvious.

The next subsystem (Figure 3) is the ground data acquisition station with its antenna, receivers, decoding, display and command equipment. From locations to which adequate ground communication links are available, it is our practice to transmit the information, received at the remotely-located data acquisition station, directly to the central control center at Goddard. This enables key command decisions to be made at a location where it is feasible to assemble the scientists familiar with the experiments, and the engineers familiar with the spacecraft subsystems. Spacecraft simulators and ground computers, which it would not be feasible to put at each of the remote ground stations, can also be used to aid in determining operating procedures as required by spacecraft and experiment status.

The primary output of the data acquisition station is the magnetic tapes on which the raw encoded data received from the satellite are recorded. This is shipped to the Data Processing Line whose function it is to decode and digitize the raw data and put it in a form that is physically meaningful to the experimenter. The resulting digitized data, along with related orbital position and spacecraft attitude information are turned over to the experimenter whose responsibility it is to perform the data reduction and analysis. Here again there is a strong inter-relationship between the "Processing" and the "reduction and analysis" subsystems. Both call for the use of relatively large digital computers and the output from the processing line must be compatible with the planned data reduction process.

The ultimate in efficiency would be a merging of these two subsystems. This calls for a very close relationship between the experimenter and the data processing line designer, and some foreknowledge of the character of the data, which generally is not available in the case of the more exploratory type of experiments. It is, therefore, clearly desirable for the "processing" line to have a flexibility that will enable it to perform a broad variety of the computation and plotting operations that might be required in the performance of the "reduction and analysis" function.

DESIGN CONSIDERATIONS

Before discussing the Earth-Satellite data system which is now being operated by the Goddard Space Flight Center, it will be useful to examine the factors that strongly influenced the design of this system.

The most significant factor that influences the design of any satellite data system is the fact that the phenomenon being studied cannot be turned on and off by the experimenter. This is in contrast with most Earth-bound experimental facilities. For instance, in a wind-tunnel the data system is operative only during the interval when the model is exposed to a moving air stream. In a particle accelerator one makes observations only during the period of high-energy particle bombardment. The space experimenters, on the other hand, want to observe the effects of a solar flare, the impact of the solar wind on the magnetosphere, or ionospheric effects associated with an auroral disturbance. They cannot turn these phenomena on or off at will. Thus, a major portion of the data-perhaps as much as 99% in some cases-merely furnishes a background level against which to measure the effect of the occasional disturbance that is the subject of the experiment. This implies two things:

(a) The data acquisition system must be in continuous operation to assure that it will be operating when the disturbance occurs; this accounts for the huge mass of data that is required.

(b) The data processing technique must be such as to permit quick scanning of the results so that the time interval of special interest can be identified, and the data in these sections subjected to special analysis. This requires, in the first place, a "production line" processing to put the data in a condition that will make it physically meaningful to the experimenter. It also places emphasis on means for quick scanning of the data to identify the areas of special interest. The latter portion of this paper will deal with progress that has been made along this line.

This is part of the data system on which there is need for further development and adaptation of display techniques to fit a variety of requirements.

A second characteristic that dominates the design of a satellite data processing system is the "non-optimum" character of the received signal. Production line processing of a clean, noise-free signal is desirable, however, for a number of reasons—limitation on weight and radiated power, unfavorable combinations of orientation and antenna pattern, auroral disturbances, plus the hard fact that in a disturbing number of instances the onboard system does not work quite as its design called for—the received signal may be extremely noisy on occasion. The data processing system must be designed to handle such a degraded signal which may look as bad as the one shown on the top of Figure 4. A signal conditioning system must be devised which will dig this signal out of the noise, reconstitute it as shown on the second line, put it in digital form as on the third line, and perform a quality check to assure that spurious signals have not been accepted. The automatic means of doing this is the heart of the data processing line in operation at Goddard.

A third characteristic is the "general-purpose" nature of the satellite data processing system. It is not economically feasible to build a special-purpose system tailored to the individual needs of each satellite and experimenter. Furthermore, it is not practical, since most of the experiments, sensors, and data requirements that the system will eventually have to support are not identified until after the data processing system is designed and becomes operative. Thus, the system cannot be optimized in terms of taking into account specialized data compaction techniques, or onboard data processing techniques that might be used on one satellite or class of experiments, but not another. The design must be a "least common denominator" type, with some sacrifice from the optimum for any given use, in favor of an adaptability to a variety of uses. This consideration has led to the choice of a Pulse Code Modulation type of satellite telemetry system, using a binary coded digital system for data transmission. This system may not be as "efficient" as some alternatives but it is readily adaptable to a variety of uses, with special advantages for real time readout.

This consideration has also led to the use of a relatively large digital computer in the data processing line, rather than smaller special-purpose computers which might have been chosen. The capacity of the computer not only gives the desired flexibility, but also provides a capability for expansion into the "reduction and analysis" part of the system, previously mentioned as highly desirable. This latter capability is considered to provide a potential for increased efficiency in the data analysis process. In order to exploit it, a very close collaboration has to be built up between the experimenter, the equipment designer and the programmer. Generally this is not feasible until actual data is available to the experimenter so that he can choose appropriate analytical techniques and computational processes. The large scale digital computer, rather than smaller types, provides the capability of coping with these requirements as they develop.

DESCRIPTION OF THE GODDARD DATA SYSTEM

As shown on Figure 5, the data system is in four separate locations-the spacecraft, the data acquisition station, the Central control station at Goddard, and the data processing area at Goddard. This system operates in two modes. The first is a real-time mode. This includes the command portion of the system, and the data transmission and receiving portion. They are inter-connected by radio or microwave links and are operated in somewhat of a closed loop fashion, during the time the satellite is passing over the ground station. The data processing function is a completely separate operation, and is the first step in putting the data into a form suitable for analysis by the experimenter.

Real Time Data Acquisition Operation

Figure 6 shows the real time components of the operation in somewhat greater detail.

Once the spacecraft is launched, and appendages carrying experiments deployed, the experiments as well as certain housekeeping data sensors indicating such quantities as spacecraft temperature, battery voltage, solar aspect, etc., will go into operation. The resultant sensor outputs are encoded and stored on onboard tape recorders or are transmitted directly. When the spacecraft comes up over the horizon, it will be first commanded to transmit data so that its status can be determined, and the ground operators can be assured that the spacecraft is in its normal operating condition; experiments operating and on scale, etc. These data will not only be immediately decoded and displayed at the Data Acquisition Station, but also at the Goddard Control Center. At this latter place are located both the spacecraft engineers and experimenters. Displays are immediately presented to them which enable them to judge whether the piece of equipment they are responsible for is operating normally or not. Based on this information, a decision is made as to the desired mode of spacecraft and experiment operation.

The OGO spacecraft, shown on Figure 7, carries some twenty experiments some of which are specially designed for low-altitude perigee data, others for high altitude apogee data. Some of these are very low data rate gatherers such as the micrometeorite detector which requires only a periodic count of the integrated number of micrometeorite hits. Others, such as cosmic ray counters, have a varying data rate dependent upon the satellite position in space. Many of the experiments incorporate the capability of changing scale ranges, to adapt to the magnitude of the quantity being measured at any given time. To cope with this variety of situations the command system has a capability of 256 different commands calling for various combinations of spacecraft and experiment operation. One such command turns over the entire telemetry link to spacecraft functions only and is used for emergency diagnosis of the status of the satellite. On other occasions, experiments specially appropriate for an anticipated perigee pass will be turned on, others turned off.

The command can be encoded either at the Central Control Center at Goddard, or under more routine situations, at the Data Acquisition Station. It will be received by the spacecraft, responded to, and the results observed in real time at the Control Center. The results to be meaningful, and to permit command decisions, generally must be converted from digital to analog form and displayed on strip charts-in essentially real time. The experimenters then are looking at the output of their experiments in a format with which they have become familiar during the ground calibrations and checkout procedure, and can make quick interpretations and adjustments as required.

The OGO is a relatively "passive" spacecraft. Once it is launched and its orientation with respect to the earth, the sun, and the orbital plane, is established by the onboard control system, it is not controlled from the ground. In contrast the Orbiting Astronomical Observatory (Figure 8) is specifically designed for the purpose of carrying a large telescope with 36" optics which must be selectively pointed just as an earth based telescope is, in order to make the desired celestial observations. Thus, as the OAO comes in view of the ground station, its orientation must first be identified with the aid of the onboard sensor data that has been transmitted to the ground; then reorientation commands transmitted as appropriate for the next observation. Early in the design of the satellite a choice had to be made as to where to put the command and computation equipment necessary for such a reorientation maneuver; on board the satellite, or on the ground. In the interest of decreasing satellite complexity and increasing reliability it was decided to do this on the ground. These reorientation commands thus will be originated at the Central Control Center shown in Figure 9 and transmitted to the satellite in relatively simple form requiring no onboard processing. The appropriate control commands, which call for a specific number of turns of inertial wheels on board the satellite, will be determined with the aid of a simulation of the dynamics of the spacecraft and its control system on a large scale digital computer at Goddard, adjacent to the Control Center. The observing astronomer, having chosen the new object that he wishes to observe, will with the aid of this simulator be able to determine the appropriate slewing commands required to reorient the spacecraft—and will be able to observe both the spacecraft change of attitude and the operation of his observing telescope, from real time displays at the Control Center. Thus, he will be in direct control of his observing program just as he would be in a ground based observatory.

The equipment used to perform the above described acquisitions and command steps is shown in Figures 10a and 10b.

Data Processing

Tape Evaluation—Turning now to the "data processing" portion of the operation, Figure 11a shows the successive steps in this sequence. These start with the receipt of the tape, forwarded by mail from the data acquisition stations throughout the world. Upon receipt of the tapes, they are logged into the station tape library and prepared for disbursement to the following operations. This figure highlights the first step which consists of the initial tape evaluation. This step not only rules out obviously defective or misidentified tapes, before starting the automatic data processing operation, but also serves the very useful function of keeping the station operators on their toes. Comparative scores as to the defective tapes due to operator error, are kept on the various stations and by this method a psychological situation is set up which helps keep down these errors. No station likes to stay on the bottom of this list for two months in a row. As a result, stations place considerable emphasis on their own self-checking procedures and catch repetitive errors before they can cause extensive loss of data.

Decoding and Digitizing—The second step, Figure 11b, has been previously referred to as the heart of the automatic data processing system. The input signal to be processed was shown in Figure 4. The received signal from the PCM telemetry transmitter is a two level square wave signal with the lower level indicating the "zero" and upper level the "one" of a binary coded bit. A typical received signal distorted by noise is shown on the top of Figure 4; the reconstituted signal after the filtering process is also shown; and the digitized code of "zeros" and "ones" into which this signal is converted for printout on the output digital tape.

Equipment used to do the processing in this stage is shown in greater detail on Figure 11b. On the left are the tape drives on which the reels of tape recorded at the data acquisition stations are mounted. Two are used to improve operational efficiency. The adjacent three racks of equipment, commonly referred to as the "front end", perform the functions of digging the signal out of the noise and reconstructing it in a perfectly clean form; synchronizing with the data stream; identifying unique frame synchronous words; and formatting the data into, for the case of OGO, 128 word frames with nine bits apportioned per word. It additionally provides signals for interrogating the next three racks which are the time decoder. The time decoder, utilizing signals recorded on other tracks of the station tape, reconstructs and presents the time at which the data was received at the recording station in days, hours, minutes and seconds plus other identifying information.

The same techniques have been adapted for use on other types of telemetry systems, one of which is the Pulsed Frequency-Modulation (PFM) system used on the smaller satellites of the Explorer series. This produces a frequency analog of the sensor output rather than the two level square wave signal produced by the PCM telemetry. The PFM input signal covers a 3,600 cycle/sec to 16,400 cycle/sec frequency range. Thus in place of two levels typical of the PCM signal, the signal processing system must identify 128 levels of the analog signal and convert them to digital form. A "comb-filter" technique adapted from radar technology is used for this purpose. A bank of 128 filters tuned at intervals of 100 cycles, each with a bandwidth of 100 cycles, covers this range of frequencies. By sensing which of the filters has the greatest output a determination is made of the unknown incoming frequency to within 1%. The output is thereby digitized into one of 128 levels.

The output from either of these processes along with time and other identifying information is recorded on the tape on the right hand rack on Figure 11b. The resultant format of the digitized tape is shown on Figure 12. This is a magnetized digital tape capable of providing the input to most digital computing machines. The filled in squares on this tape indicate "ones," the open squares "zeros" of the binary code. Each 128 word frame of this tape includes the time of the start of the frame, an identifying code, and then the "words" which present in digitized form the output of the experiment sensor on board the satellite.

Quality Control, Decommutation and Scaling—This is the step in the "Data Processing"; the equipment on which it is done is shown on Figure 11c. This consists essentially of a large-scale digital computer which is used to examine and format the data from the digitized tape produced by the previous step. This tape is examined for bad or missing data points, time is checked, error indicators are analyzed and a new tape is made. This tape then becomes the "master tape" on which all data from the satellite is stored and preserved for later reference. It is comparable to the files and plates of an astronomical observatory on which the original data is stored. It provides a permanent reference file not only for the original experimenter—but also any later investigator who wishes to analyze the data from a different viewpoint. This tape, along with an "orbital tape" which records the satellite position and orientation at any given time is kept on permanent file for reference at the Goddard Data Center.

The data processing step is to strip out or "decommutate" from this master tape the data of interest to a given experimenter. This is recorded on a new set of "experimenter" tapes and along with a separate tape which correlates time with orbital position, attitude and other reference data, provides the experimenter with all of his data in a form suitable for input to most digital computers. Dependent on the experimenter's desire, a calibration can be applied to the data in this step; in this case the data is presented to the experimenter in terms of the engineering units appropriate to the physical quantities originally detected by the experimenter's sensor.

Data Reduction and Analysis

At this point the "Data Reduction and Analysis" passes under the control of the individual experimenter. The processes involved are a function of both his needs and the computing and plotting equipment available to him. However, in almost every case he will be called upon to perform the steps depicted in Figure 13, with the last step, the visualization of the data, playing a most important role in the digestion and understanding of the large mass of data.

The important point is that the "experimenter" tapes produced by the previously described digitizing processes are in a format adaptable to large scale digital computers. It is thus readily feasible to make full use of these computers and the variety of automatic plotting and display devices that can be driven by them. The effectiveness of the adaptation of this equipment to the analytical needs of the experimenter is generally dependent on the close collaboration between him, the equipment designer, and computer programmer. Some specialized adaptations that have evolved from such a collaboration are described in the following examples.

Correlation of Tiros Infra-red Data with Cloud Pictures—The Tiros weather satellites have produced a larger mass of data of a repetitive nature than any of the satellite programs handled by Goddard. As a result methods of machine analysis of these data have been most extensively developed. A specific example is the machine process whereby the data from the infra-red radiation sensors is digested and plotted in a form that facilitates comparison with the cloud pictures taken by the television type (TV) cameras on this satellite. In this case, each infra-red data point is representative of an effective black body temperature of a spot on earth viewed by the radiometer. When viewing directly downward from the height of 780 km, which is typical, this "spot" has a diameter of 68 km. To enable the experiment to make an analysis of the huge mass of data thus obtained on each earth orbit, a rapid means has been developed, with the aid of a large scale digital computer and associated plotting devices, to put these data in "pictorial" form for direct comparison with the TV cloud pictures taken by the Tiros cameras. With the aid of such a comparison the analyst is then in a position to focus his attention on a more selective group of data directly pertinent to the phenomena he desires to study. Figures 14 to 19 show the successive steps whereby this procedure was applied to the cloud temperatures peculiarities associated with a hurricane.

A TV cloud picture taken of Hurricane Anna, the final hurricane during the 1961 season, is shown on Figure 14. Superimposed on this picture is a ground map projection of the Northeast coast of South America. The cloud formation in the upper right is that associated with Anna. At this point in time, 15:50 GMT on July 21, it was centered about 70 miles north of Guajira Peninsula, with the Columbia coast line running laterally to the west and joining Panama.

The "processed" IR data for the same area was stored in digitized form on a tape similar to the one shown on Figure 12. A second tape contained satellite position and attitude data sufficient to identify the spot on the earth being viewed. A third tape contained the conversion factors required for converting the digital information to meaningful terms, in this case °K.

Appropriate computer programs were prepared to process these tapes. One of these programs averages the temperature readings in any given 2.5° latitude/longitude square on the earth's surface; this will be an average of from one to 60 readings, depending on the satellite position and look angle at the earth when the IR scan is made. An automatic print out of this temperature distribution over the same geographical area of the cloud pictures of Figure 14 is shown on Figure 15. For squares in the mesh where no data exists the average temperature for the entire mesh (270°K in this case) is printed. In other meshes the average value for that 2.5° square is printed. Also printed are "grid filler" numbers (5's, 6's and 7's in this case) which are later used as an aid in contouring at 10°K intervals.

The next step accomplished by the computer is the overlay of the ground map projection (Figure 16). The temperature gradients associated with the eye of the hurricane in the region north of the Guajira Peninsula now become evident.

The final step performed by the computer is the drawing of the contour lines shown on Figure 17. The sub-satellite path is also superimposed on this map. The time required by the computer-plotter combination to perform the steps shown in Figures 15, 16 and 17 is not much longer than it takes to describe it; the elapsed time to perform these steps is about 15 minutes.

The final result, which emphasizes the pictorial nature of the presentation, is shown on Figure 18. (This is the first step in which the human hand gets involved; we have not yet programmed the computer to do the coloring or shading between the contour lines.) From this figure the uniquely low temperature conditions associated with the eye of the hurricane stand out. The analyst now is able to focus on the directly pertinent data in an attempt to achieve an understanding as to the physical processes involved.

A more extensive global plot, put together from seven orbital passes on July 16, 1961, is shown on Figure 19. Many interesting meteorological phenomena including not only Hurricane Anna but three additional tropical storms, polar fronts, the tropical convergence zones, and the hot cloudless areas become evident from a detailed examination of this figure.

Study of Heat Balance in the Earth-Atmosphere System from Tiros IR Data—The radiation measurements made on the Tiros satellite include two channels which measure the reflected energy (the earth's albedo) and three channels measuring radiation in longer wave length. When the reflected power density is subtracted from the solar input (2 calories/cm^2/min), the difference is a measure of the energy absorbed by the earth-atmosphere system at the particular spot on the earth being observed. The three longer wave length channels measure the outgoing energy, from the same area, in the infra-red wave length. Such local energy imbalance as exists between this incoming and outgoing energy drives the atmospheric heat engine. The imbalance between the equator and the poles has long been recognized as having a major influence on the dynamics of large scale weather systems.

The Tiros radiation data presented an opportunity to the research meteorologist to study the regions of imbalance in greater detail than was previously possible. To do this, however, required the reduction of literally millions of points, each representative of the energy input or output from a small square on the earth's surface. A summation of these data over the 1,500 orbits during a three month period is required to study the seasonal variations in this heat imbalance. A large scale computer, and an interesting adaption of a cathode-ray plotter was used for this purpose.

The data is processed on the digital computer using as input the digital tapes similar to those described in the previous section. All points in a 5° latitude/longitude square are averaged, and then a summation is made over the three month period to get the average energy input or output per day for each square. The results are displayed on the cathode ray plotter in the manner shown on Figure 20a and 20b. Figure 20a is representative of the incoming energy, Figure 20b the outgoing energy. Ten levels of shading, for an energy range from 200 to 700 cal/cm^2/day, are represented on the figure. This shading is achieved by repeated plotting of points placed by the plotter in each square. The resulting photograph-like presentation is thus readily interpretable. The darker areas represent the higher energy flux; lighter areas the lower energy flux.

With the aid of plots such as shown on Figure 20 the meteorologist can readily interpret the data. The expected higher level of incoming radiation in the Northern Hemisphere existing during its summer months is readily observable on Figure 20a. It is also clear that there is a leveling in the distribution of outgoing energy (Figure 20b), attributed to the transport of the energy within the earth's atmosphere. More detailed examination shows a high energy input over the area of the Pacific Ocean, presumably due to lower than average cloud cover characteristic of this region. The relatively lighter shading of this same region on the outgoing energy plot, Figure 20b, indicates that less energy is going out than is coming in to this region—and thus there is a transport of energy away from this area by the earth-atmosphere-ocean system. In contrast, in the Sahara desert area there is a region of low incoming energy (presumably due to the high reflection character of the terrain), while the energy outflow is higher than normal (due to the higher temperatures and associated infra-red radiation from this area). The heat flow in the earth atmosphere is thus into the Sahara area, the opposite to that of the Pacific Ocean area.

Figures 21a and 21b present comparable data for the winter months of the 1963-64 season. The shift in the distribution of the incoming energy down to the Southern Hemisphere is evident on this plot. Detail examination also reveals a shift in the pattern of outgoing radiation traceable to a redistribution of cloud cover.

The entire computer-plotter procedure required to take the digitized data from the input tape, perform the arithmetic processing required for the summation in 5° latitude/longitude squares, and plot the results on maps such as Figures 20 and 21, takes 1-1/2 hours. Without the automatic computer and plotter aids the time required would be prohibitive, and as a result this type of meteorological analysis might not even be attempted on a routine basis.

Mapping of Earth Magnetic Field from IMP Data—Still another instance in which the visualizations made possible by a computer driven plotter most useful is the mapping of the earth's magnetic field. In this case the satellite observations were made by a highly sensitive rubidium magnetometer carried by the Interplanetary Monitoring Probe (IMP). The orbits through which this satellite traversed in relation to the earth and the magnetosphere during a six month period are shown on Figure 22. Every five minutes a measurement was made of the local magnetic field in terms of its magnitude and direction. In the course of a year this resulted in sufficient data to map the magnetic field surrounding the earth, as related to the sun-earth line, out to one half the distance to the moon. Once again the experimenter was confronted with a mass of data which must be put in a form to be meaningful.

A plot of a limited sample of these data as printed by a computer-driven plotter is shown on Figure 23. In this case the direction of the magnetic field, rather than its magnitude, proved to be more indicative of the phenomena of interest. For instance, on an anti-sun side of the earth the abrupt change in direction of the magnetic field lines is readily apparent from the arrows plotted on Figure 23. Plots of this type have been most useful in identifying the location of the neutral sheet, which was shown by the IMP measurements to extend many earth radii on the anti-sun side of the earth. The plotting technique was adapted to show regions of rapid fluctuation in the direction of the magnetic field by means of crosses rather than the arrows used in the more stable regions. It is clear from the Figure 23 that this manner of plotting clarifies the turbulent area which is characteristic of the boundary of the magnetosphere on the sun side of the earth. This turbulent region exists between the boundary of the magnetosphere, and the shock wave front formed by the impingement of the solar wind on the magnetic field of the earth.

The use of plots such as Figure 23 for other planes and components of the magnetic field provides the experimenter with an understanding of the phenomena involved. Figure 24 is a typical map which can be thus deduced showing the influence of the sun on the magnetic field.

Use of Animated Displays to Show Changing Conditions—In some instances the experimenter desires insight into the temporal change in his data, rather than the situation at a given point in time which is the normal output of the computer-plotter combinations described in the previous sections. In this case time-lapse-photography has been used. A cathode ray plotter is specially adaptable to this purpose, since successive plots can be produced on it and erased in time intervals as short as 1/30 sec. The end result is an animated plot of results which "emphasizes" the changing conditions.

Use has been made of this technique on the OGO. This satellite reorients itself on passage through perigee, and "look" angles with respect to the earth, sun and the orbital plane change rapidly during this reorientation interval. This causes transients in the on-board sensors. To enable the experimenters to visualize the cause of these transients an animated movie has been made of the spacecraft, similar to the drawing shown on Figure 25. Similar applications are under development. One possible use is a real-time presentation of the attitude and relative positions of two satellites during a rendezvous maneuver.

A second example is an animated plot of the paths of two particles, through the successive steps shown in Figure 26, which illustrates the progressive expansion of a rotating galaxy, and the formation of the typical "spiral arms".

Semi-Automatic Process for Reduction of Ionograms—The final example of the use of automatic computing techniques for data analysis is one developed for the rapid reduction of ionograms received from the Topside Sounder satellite, Alouette. These data are recorded by a number of ground stations in the photographic form shown on Figure 27. The ordinate on this photograph is the virtual height of the reflective layer as determined by the reflection to the satellite of the variable frequency transmitted by it; this frequency is the abscissa on the photograph. The analysis, which gives the electron density vs altitude, requires the readout of this ordinate and abscissa. Heretofore this reading of the film has been a painstaking process performed visually by a human. When one considers that between one and two million ionograms have resulted from the three years of operation of the two Alouette satellites, it is not surprising that a huge backlog of unreduced data has built up.

Figure 28 shows a semi-automatic readout device that has been developed at Goddard to speed up this reduction process. The ionogram is projected on the ground glass screen and the stylus at the end of the extendable and rotatable arm is used to trace the curve. The angle, θ, and radius, r, of this trace is automatically read out. The resulting analog readout is converted by a simple electronic processor to x and y coordinates which in turn are recorded in digital form on a magnetic tape. This tape then serves as the input to the digital computer on which the data analysis is performed. This mechanization speeds up the data readout process about ten fold and has the added advantage of putting the data in a form most suitable for input into automatic computing machines for the required computations. A speed-up such as this was essential if full advantage was to be taken of the unique data being recorded on a global scale from the Alouette satellites.

CONCLUDING REMARKS

In assessing the present status of the development of satellite data systems, it appears that the capability of acquiring and processing the data has outstripped the rate at which it can be reduced, analyzed and interpreted by the experimenter.

The data acquisition and processing portions of the data systems described in the first portion of this paper have been designed to accommodate certain standardized processing steps which make possible "production line" handling of the data. In contrast, the reduction and analysis processes must be "tailor made" to the analytical computations and display requirements of each experimenter.

The adaptation of automatic computing techniques in the reduction and analysis processes is essential if full use is to be made of the satellite as a research tool. In some of the instances cited in this paper it is questionable whether it would have been possible to make the analysis at all without the aid of these techniques. As a consequence, the development of automatic data analysis and display techniques assumes an importance at least equal to the development of the onboard sensors and instrumentation with which the experimental observations are made on the satellite. This situation presents not only a challenge to the data systems designer, but also implies a very close collaboration between the experimenter, the designer and the computer programmer.

ONE DAY'S OUTPUT OF SATELLITE DATA

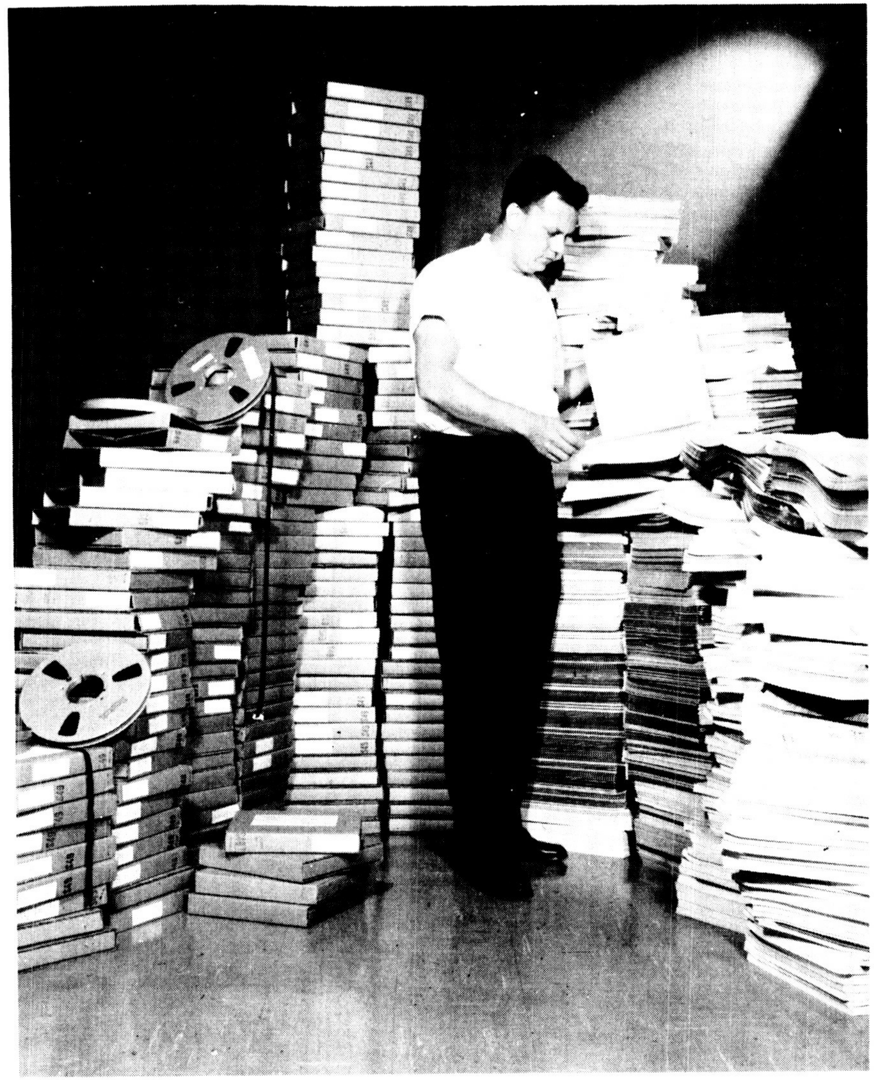


Figure 1

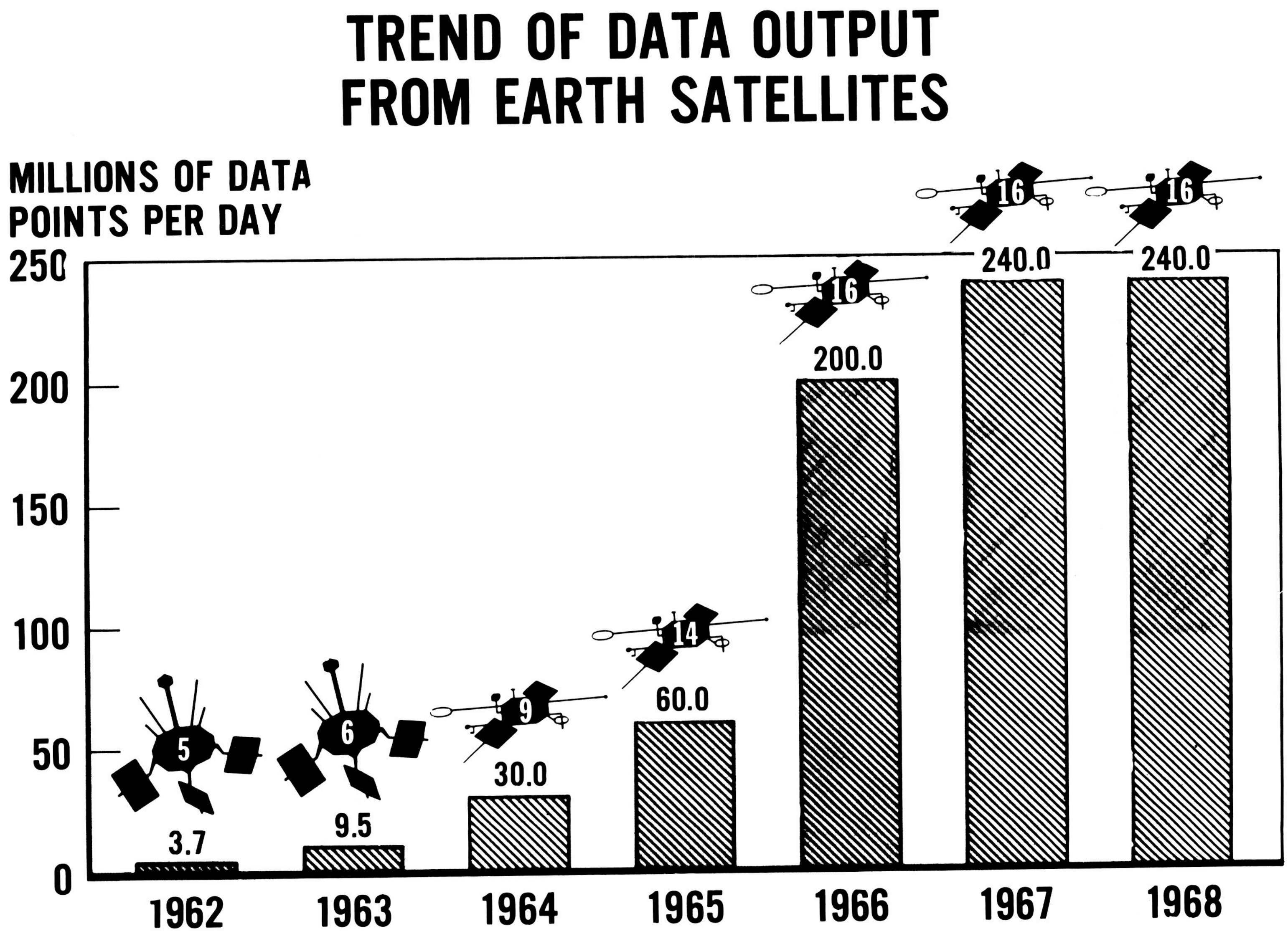

TREND OF DATA OUTPUT
FROM EARTH SATELLITES
MILLIONS OF DATA
POINTS PER DAY
250
200
150
100
50
0
3.7
9.5
30.0
60.0
200.0
240.0
240.0
5
6
9
14
16
16
16
1962
1963
1964
1965
1966
1967
1968

Figure 2

SCHEMATIC DIAGRAM OF A "DATA SYSTEM"

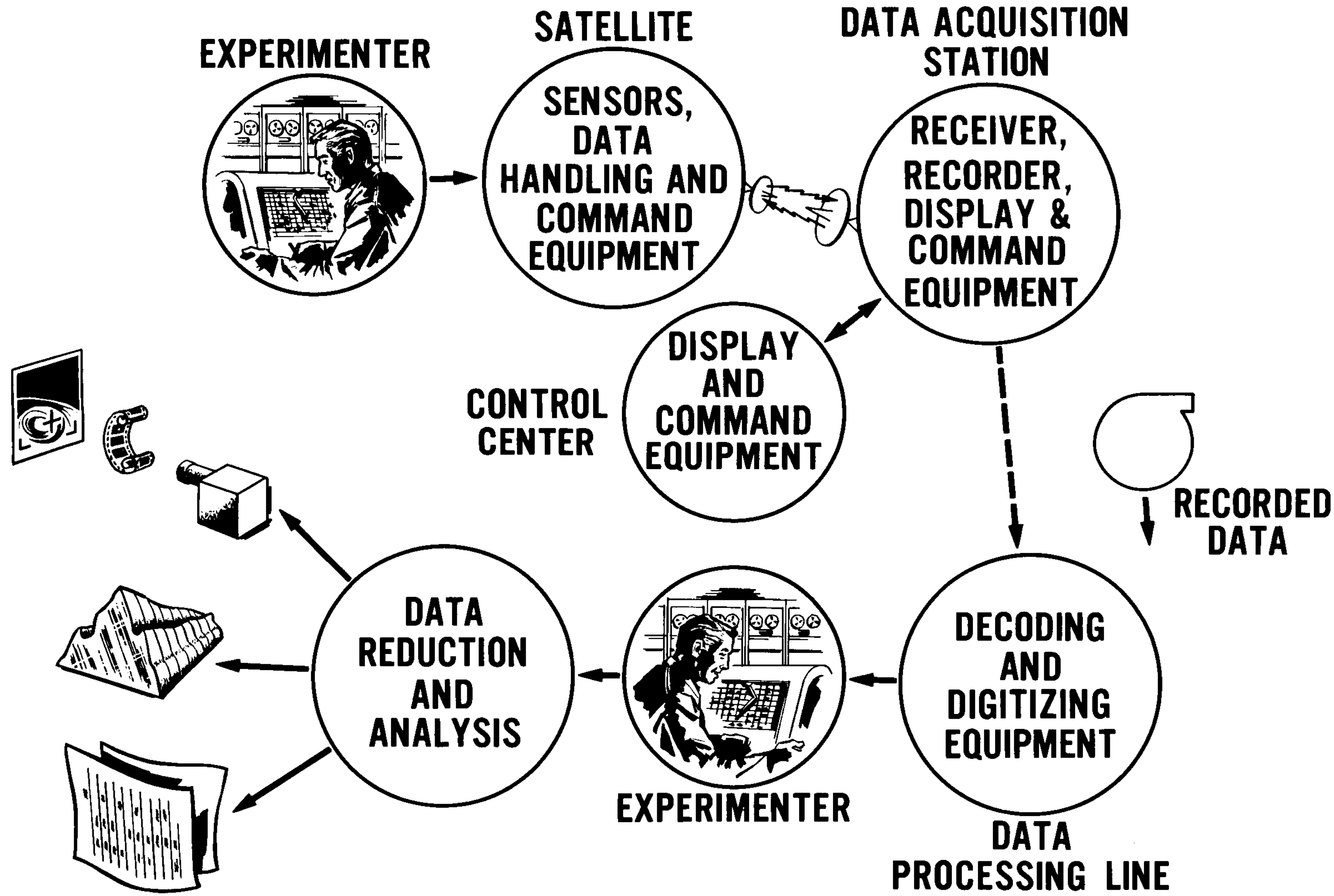


Figure 3

RAW AND DIGITIZED SIGNAL

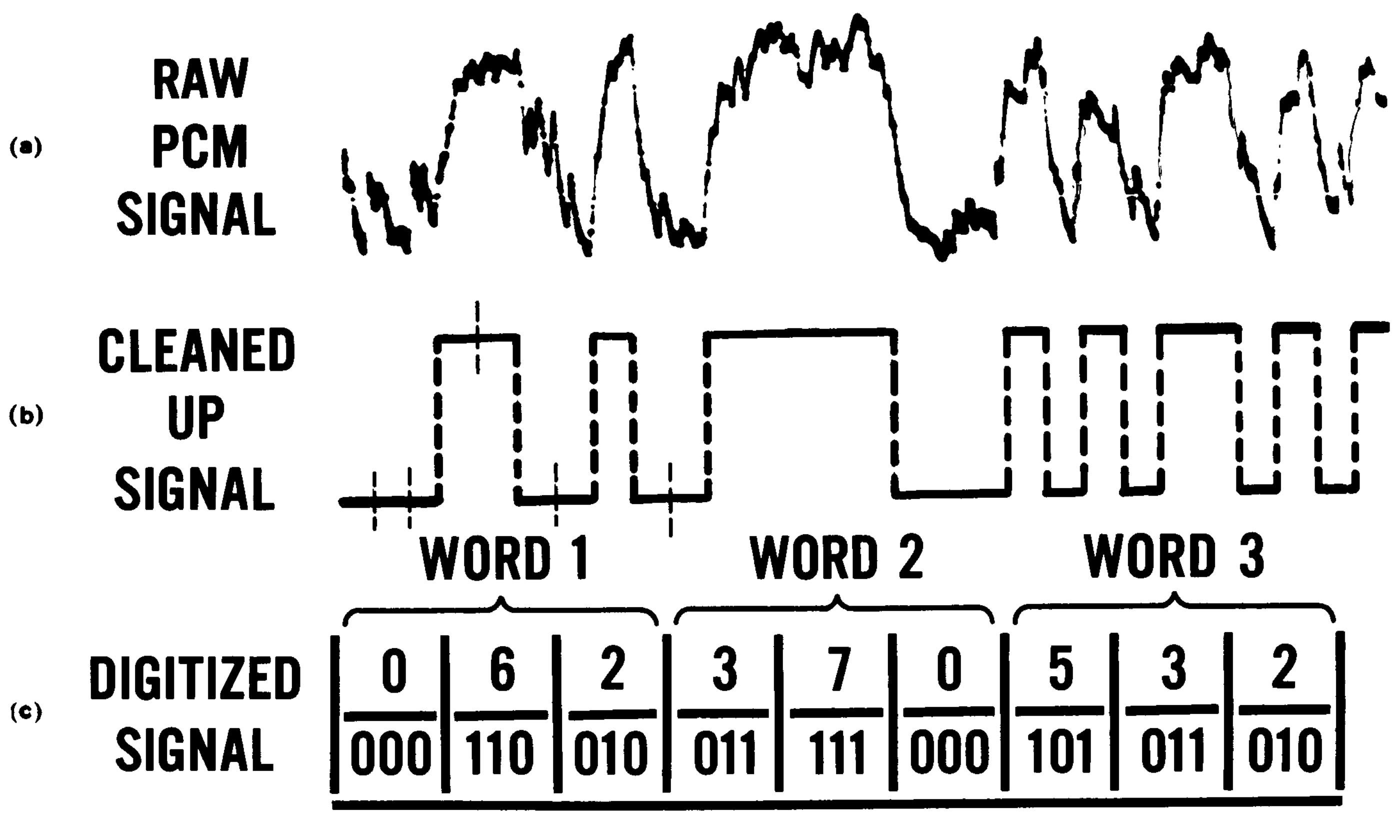


Figure 4

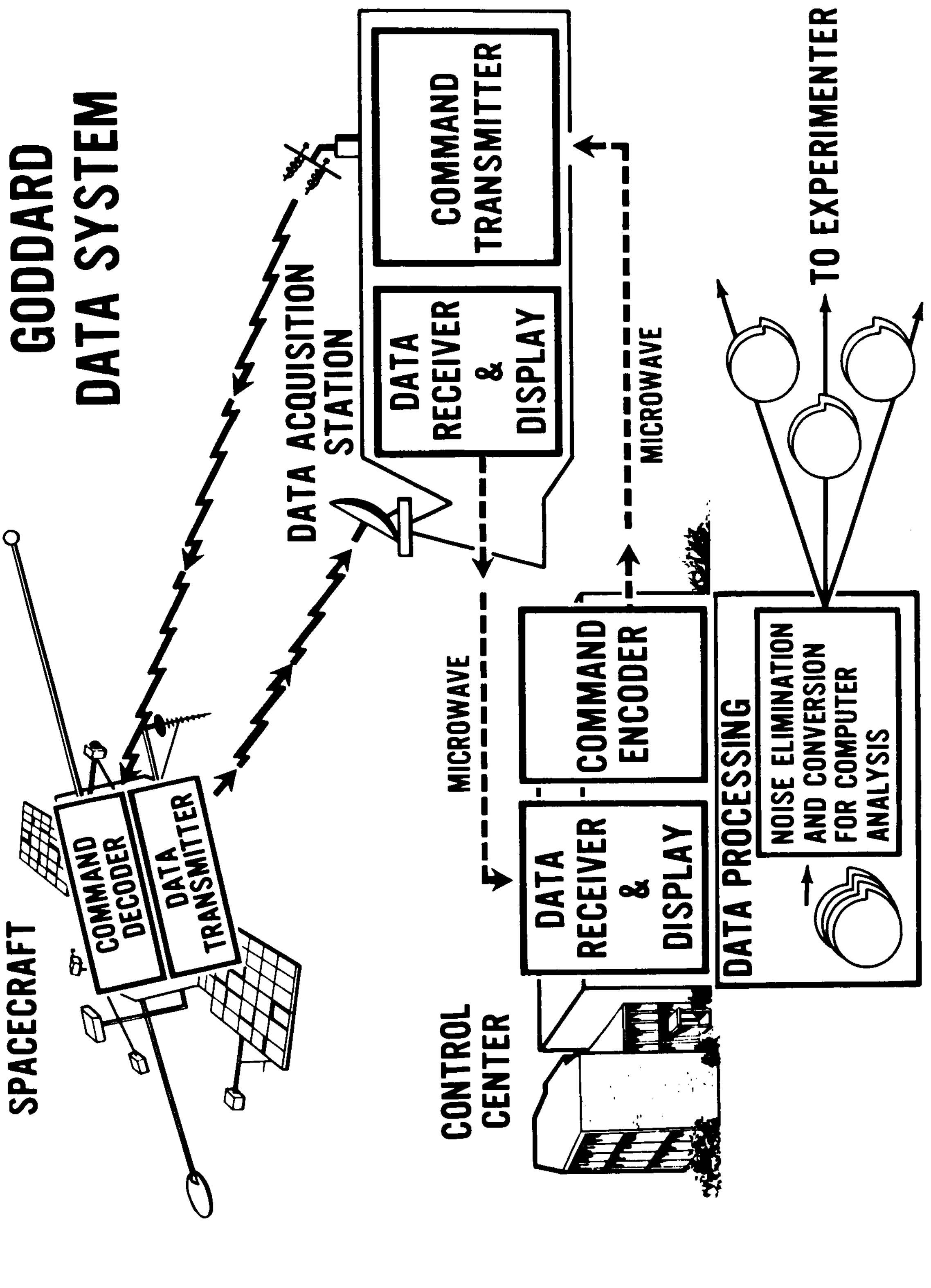

GODDARD
DATA SYSTEM
SPACECRAFT
COMMAND DECODER
DATA TRANSMITTER
DATA ACQUISITION STATION
DATA RECEIVER & DISPLAY
COMMAND TRANSMITTER
MICROWAVE
MICROWAVE
CONTROL CENTER
DATA RECEIVER & DISPLAY
COMMAND ENCODER
DATA PROCESSING
NOISE ELIMINATION AND CONVERSION FOR COMPUTER ANALYSIS
TO EXPERIMENTER

Figure 5

DATA COMMAND AND ACQUISITION SUB-SYSTEMS

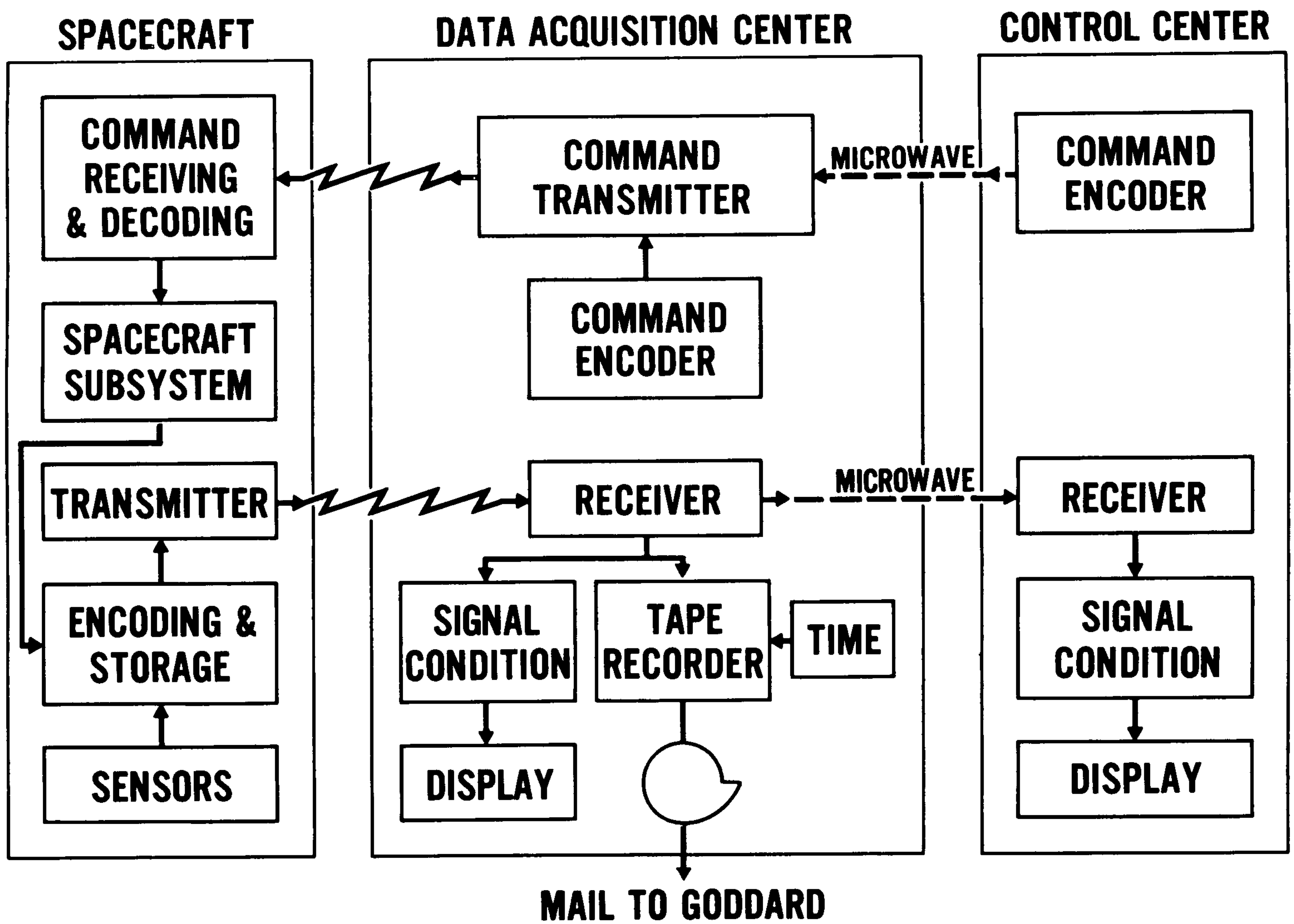


Figure 6

Figure 7

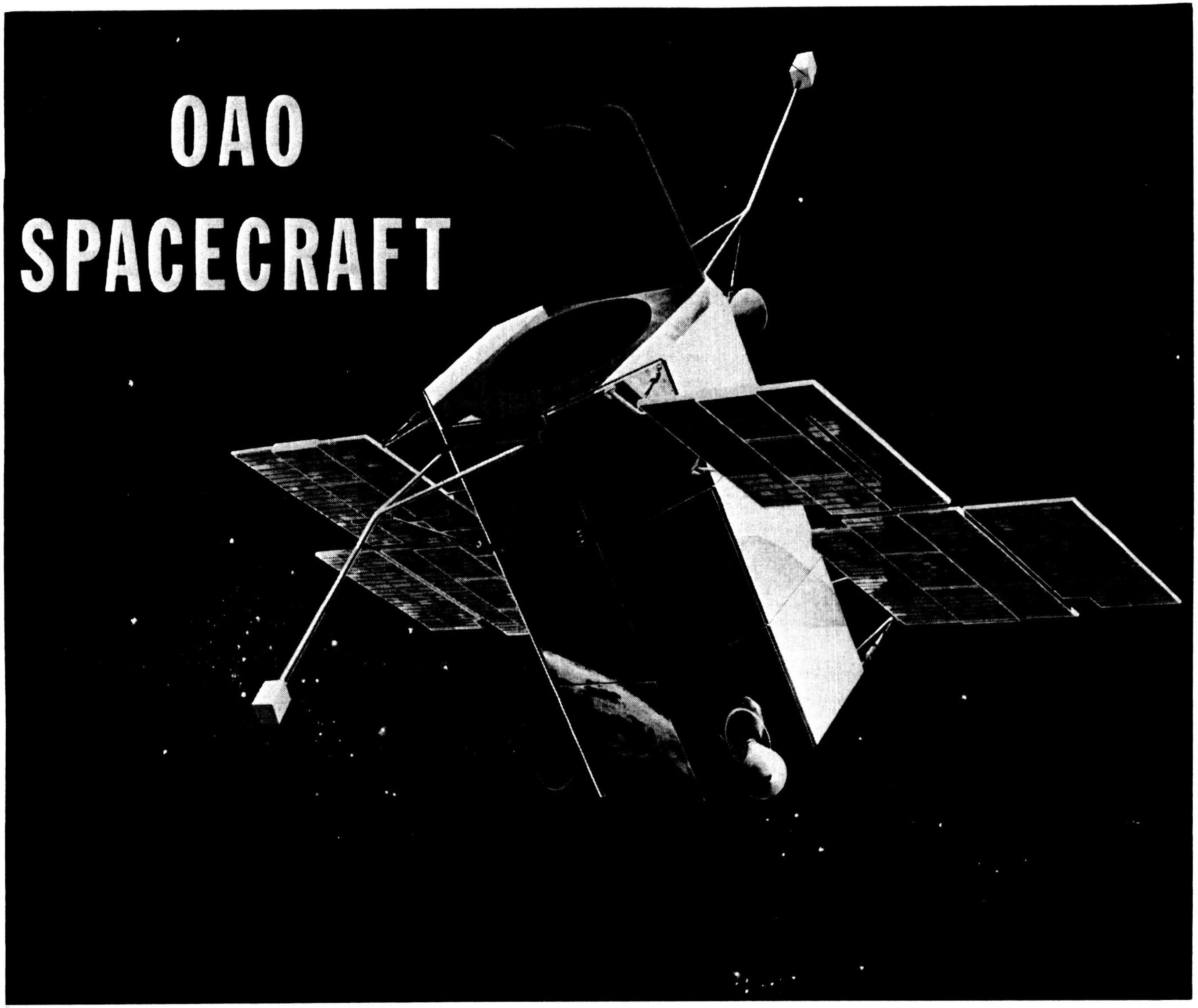


Figure 8

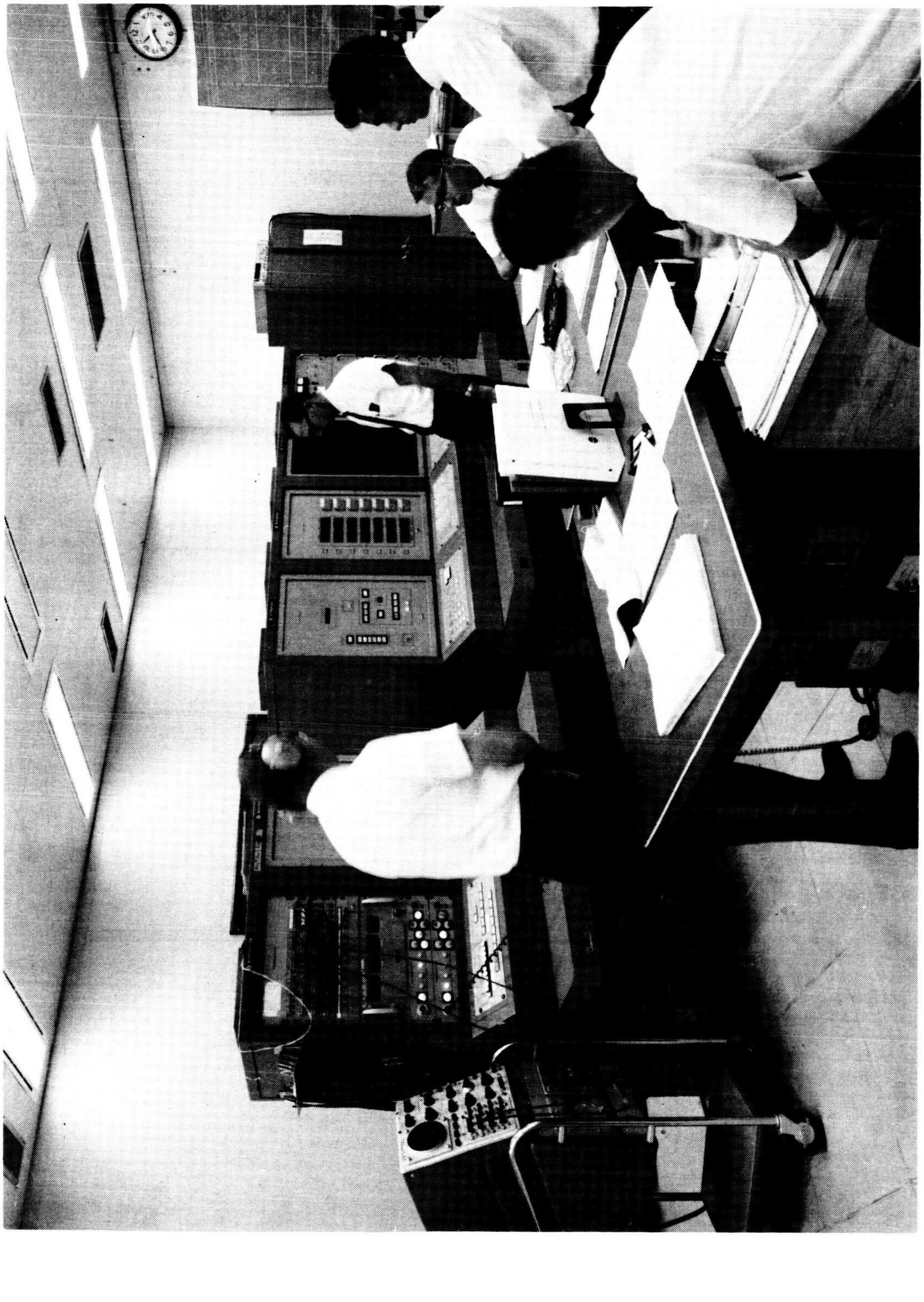
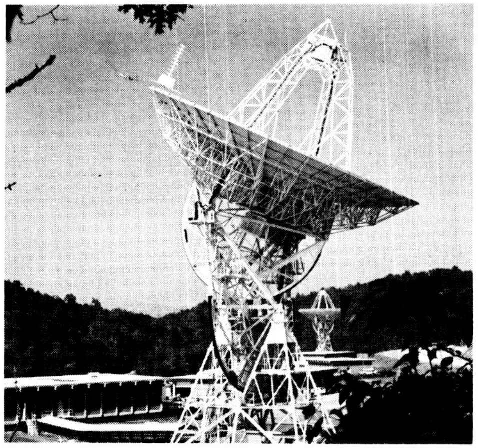
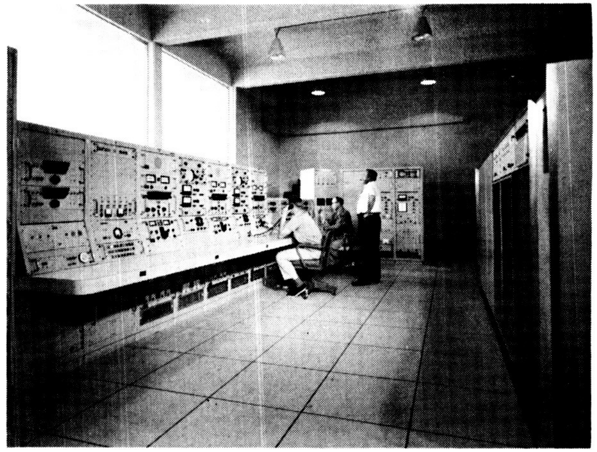


Figure 9. OAO Control Center. Command and Control Consoles



ROSMAN DATA ACQUISTION FACILITY
SHOWN ARE THE TWO 85′ DIA.
ANTENNAS USED FOR SATELLITE
TELEMETRY

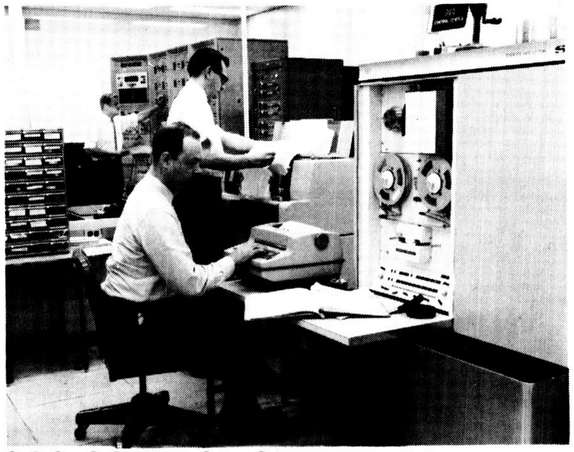


ROSMAN DATA ACQUISITION FACILITY
INTERIOR VIEW, ANTENNA CONTROL
CONSOLE

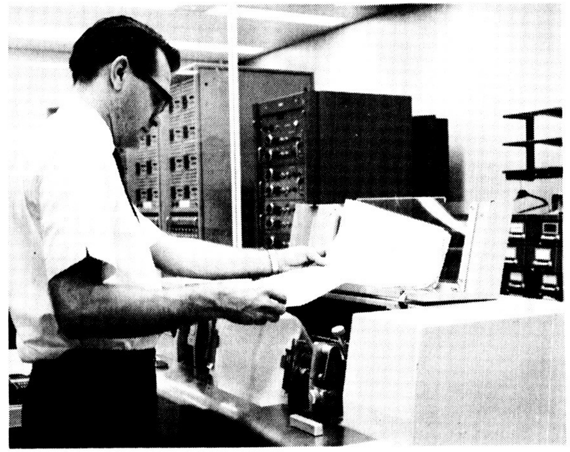
OGO CONTROL CENTER,
GODDARD SPACE FLIGHT CENTER

OGO CONTROL CENTER PCM
SIGNAL CONDITIONING EQUIPMENT

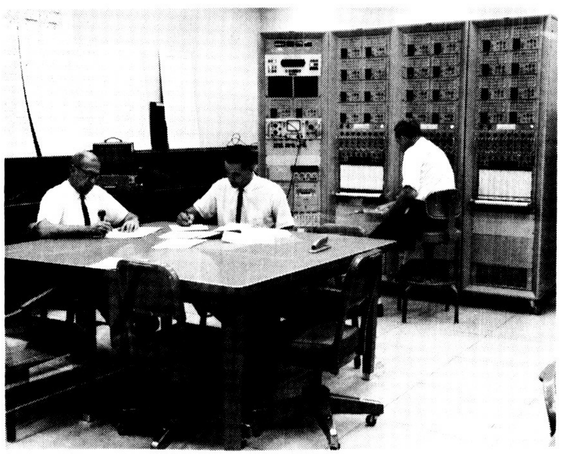
Figure 10a



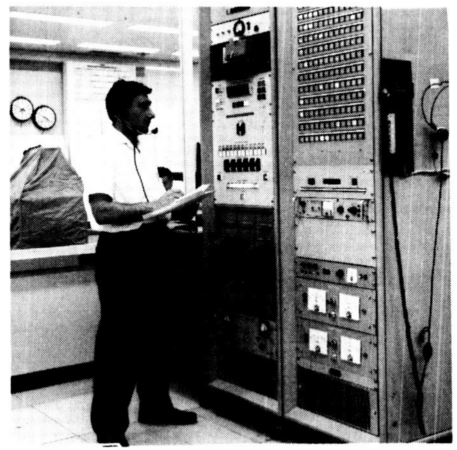
OGO CONTROL CENTER COMPUTER USED FOR CONVERSION OF DATA TO ENGINEERING UNITS



OGO CONTROL CENTER DIGITAL PRINTER FOR OUTPUT OF CONVERTED DATA



OGO CONTROL CENTER EXPERIMENTERS DATA DISPLAY ROOM



OGO CONTROL CENTER COMMAND CONSOLE

Figure 10b

DATA PROCESSING OPERATION FLOW

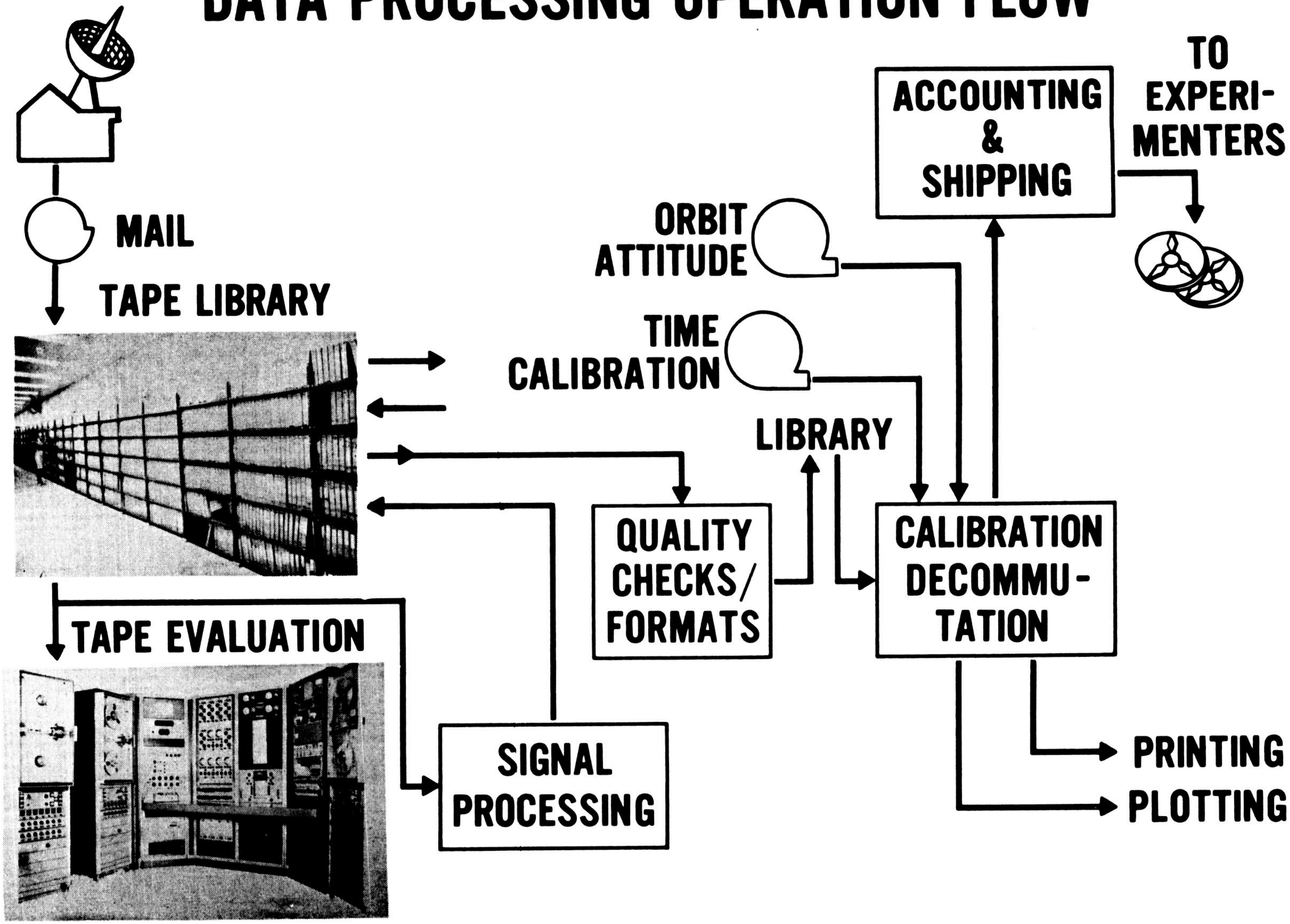


Figure 11a

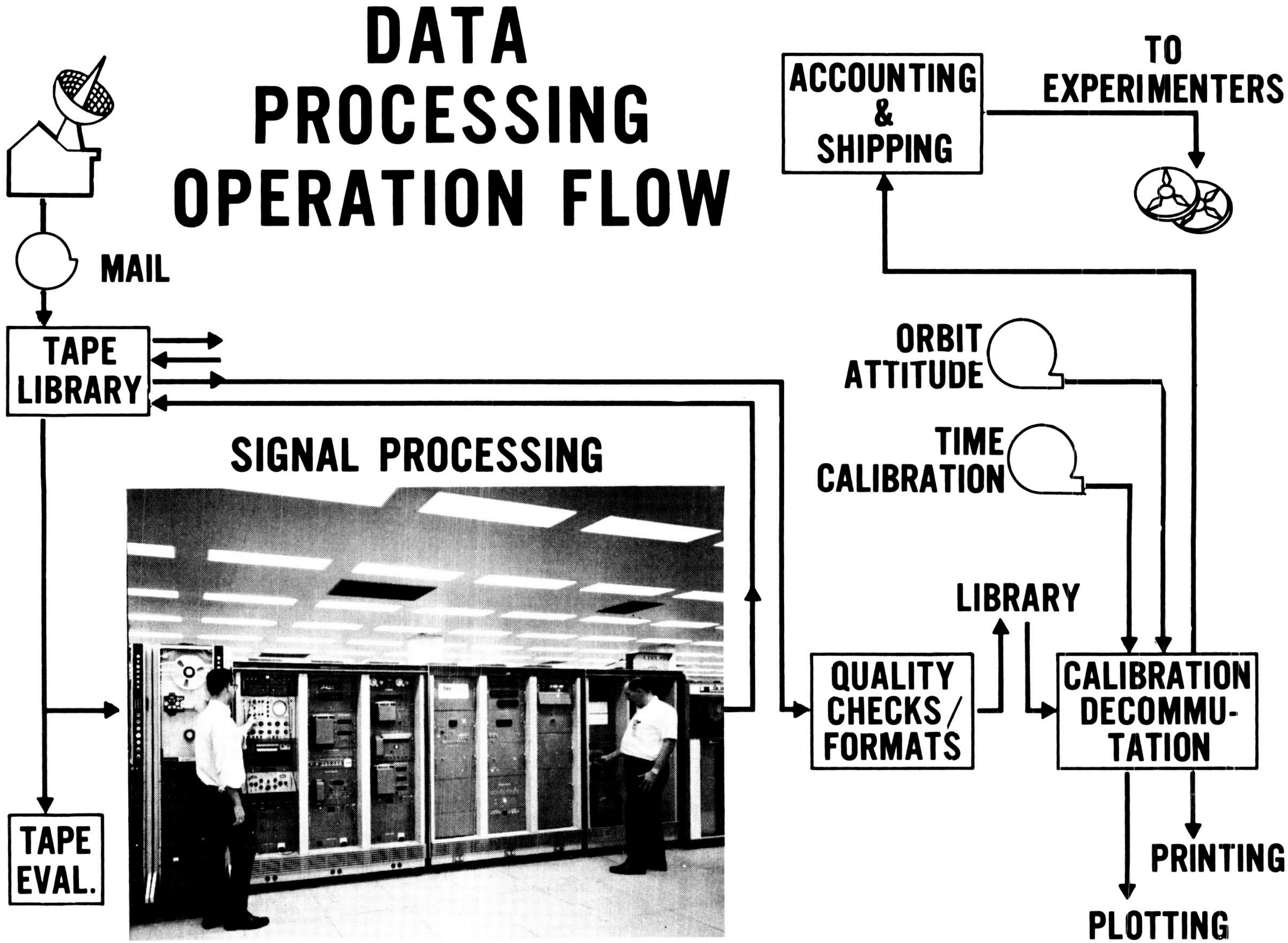
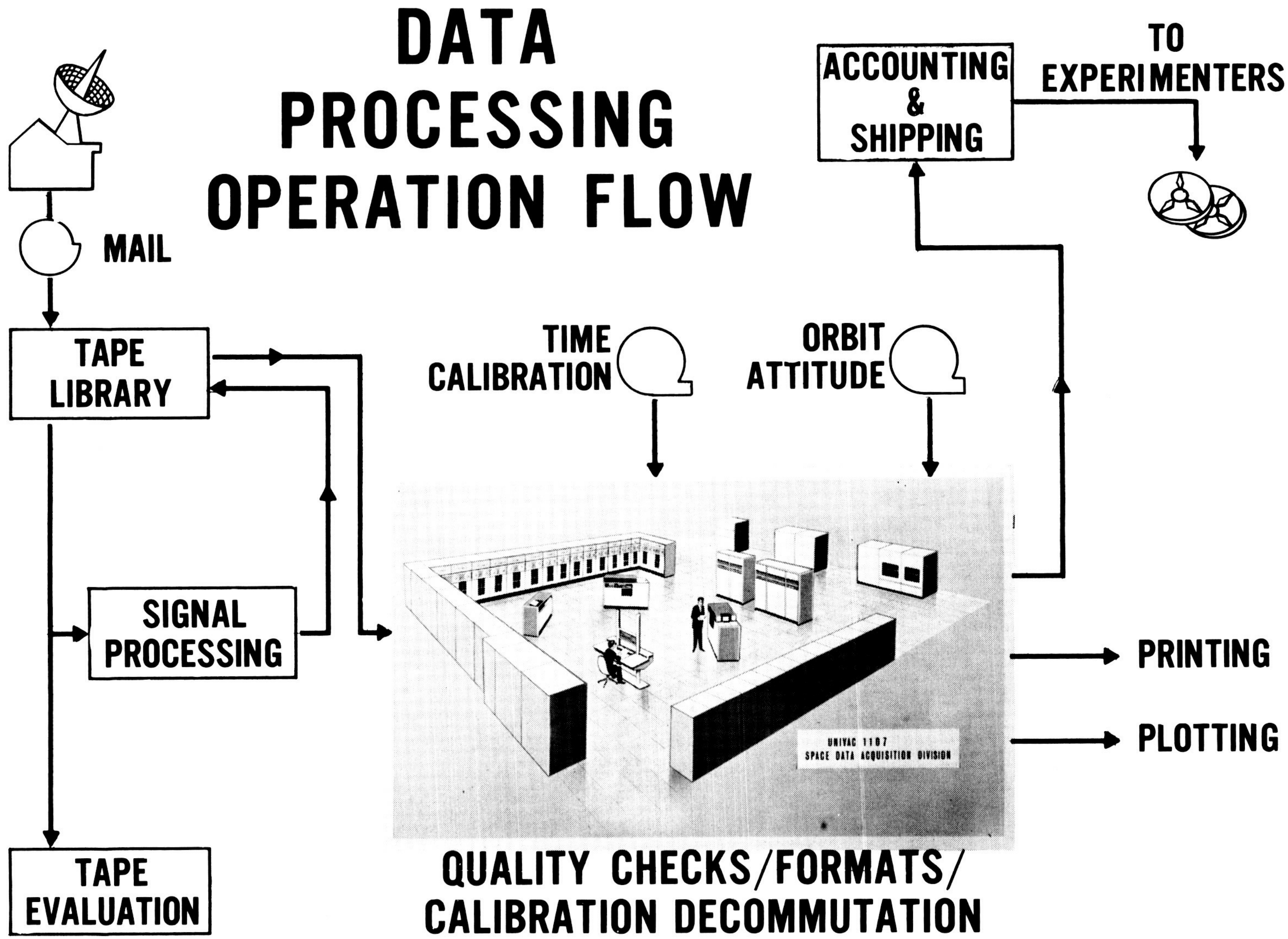

DATA PROCESSING OPERATION FLOW
MAIL
TAPE LIBRARY
TAPE EVAL.
SIGNAL PROCESSING
ACCOUNTING & SHIPPING
TO EXPERIMENTERS
ORBIT ATTITUDE
TIME CALIBRATION
LIBRARY
QUALITY CHECKS/ FORMATS
CALIBRATION DECOMMU- TATION
PRINTING
PLOTTING

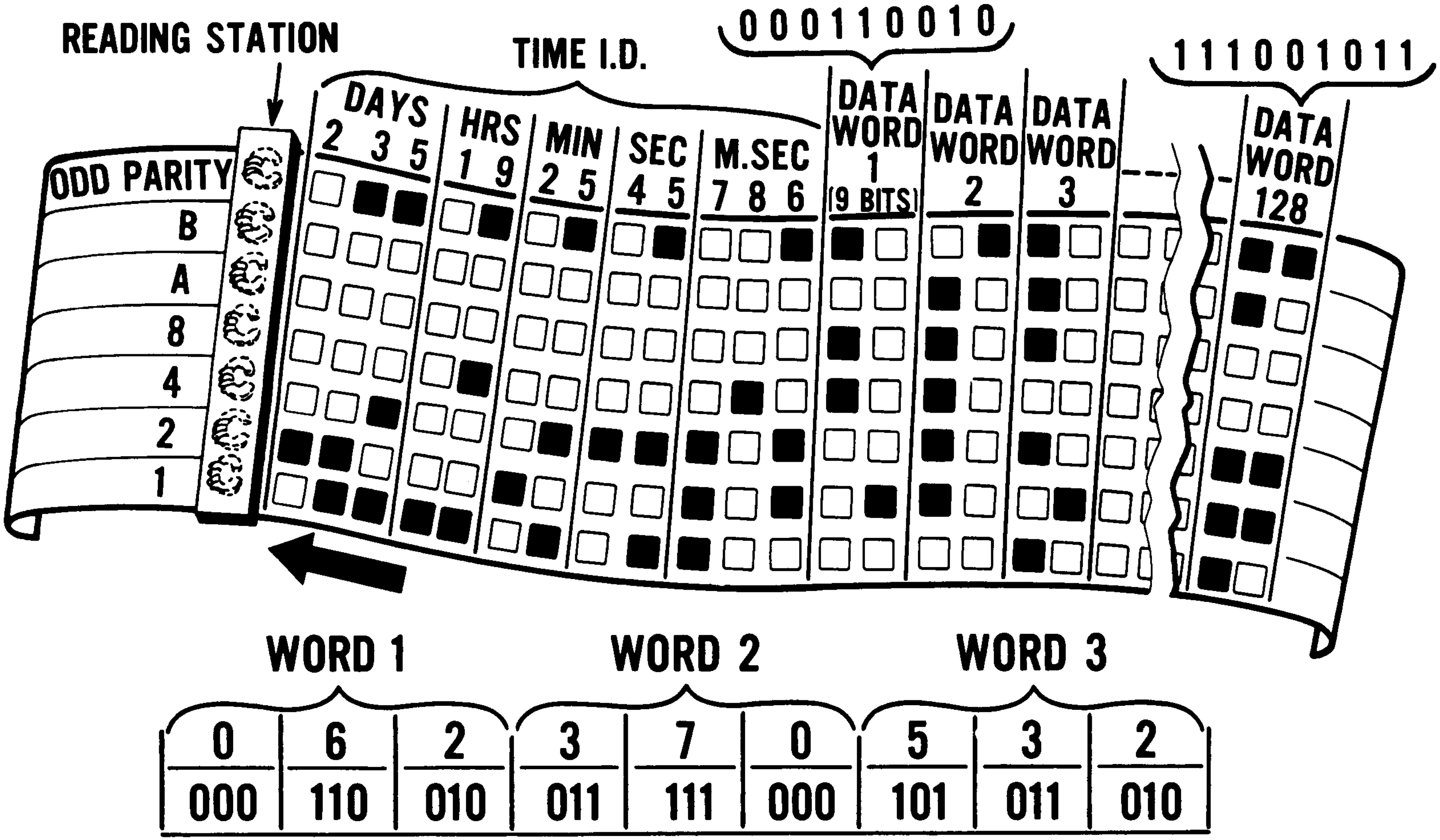
Figure 11b



DATA
PROCESSING
OPERATION FLOW
MAIL
TAPE LIBRARY
SIGNAL PROCESSING
TAPE EVALUATION
TIME CALIBRATION
ORBIT ATTITUDE
UNIVAC 1107
SPACE DATA ACQUISITION DIVISION
QUALITY CHECKS/FORMATS/
CALIBRATION DECOMMUTATION
ACCOUNTING & SHIPPING
TO EXPERIMENTERS
PRINTING
PLOTTING

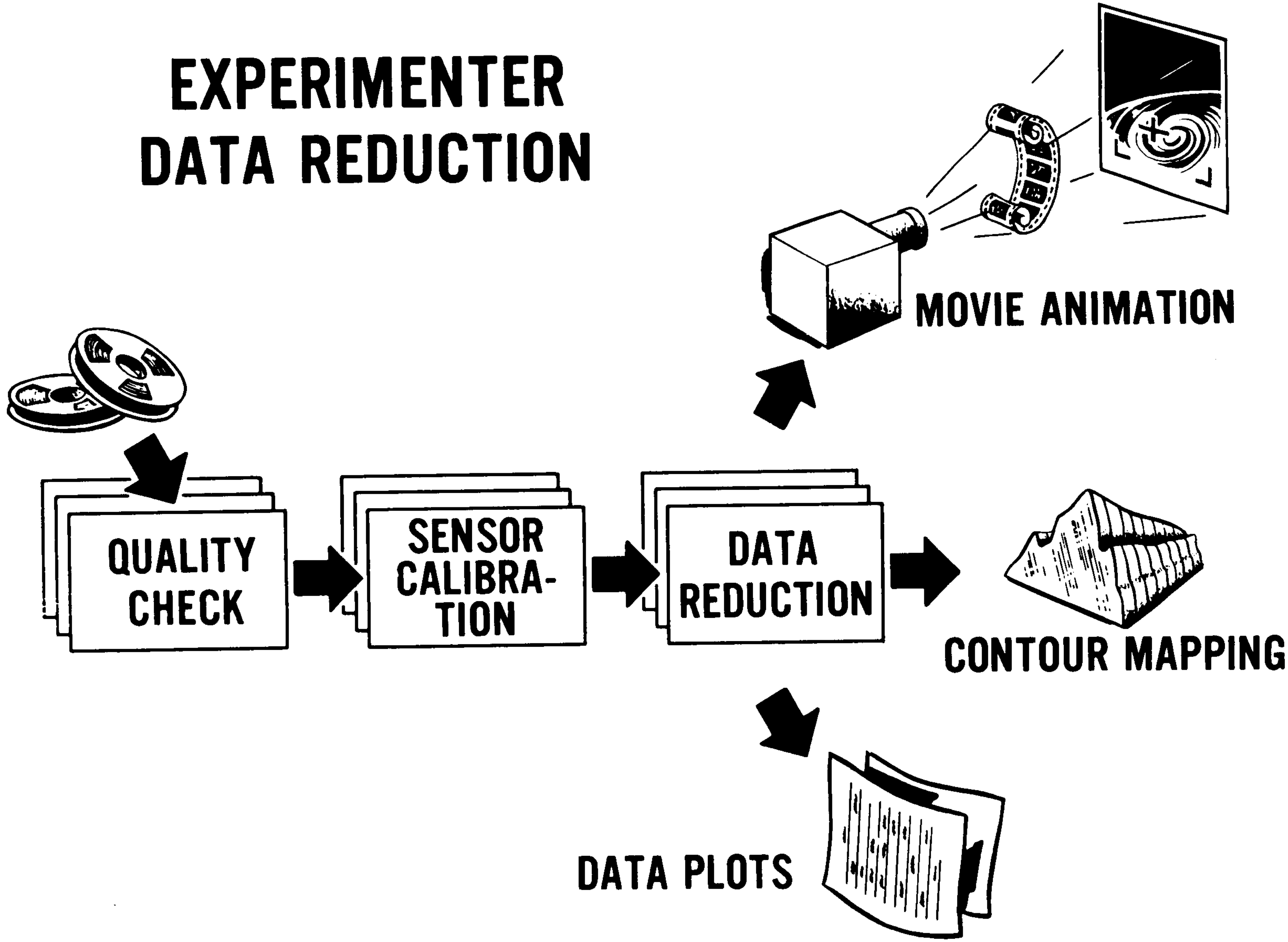
Figure 11c

DIGITAL TAPE OUTPUT FORMAT FROM SIGNAL PROCESSING OPERATION



FRAME SYNC CODE

Figure 12



EXPERIMENTER
DATA REDUCTION
QUALITY CHECK
SENSOR CALIBRA- TION
DATA REDUCTION
MOVIE ANIMATION
CONTOUR MAPPING
DATA PLOTS

Figure 13

TV PICTURE OF HURRICANE ANNA

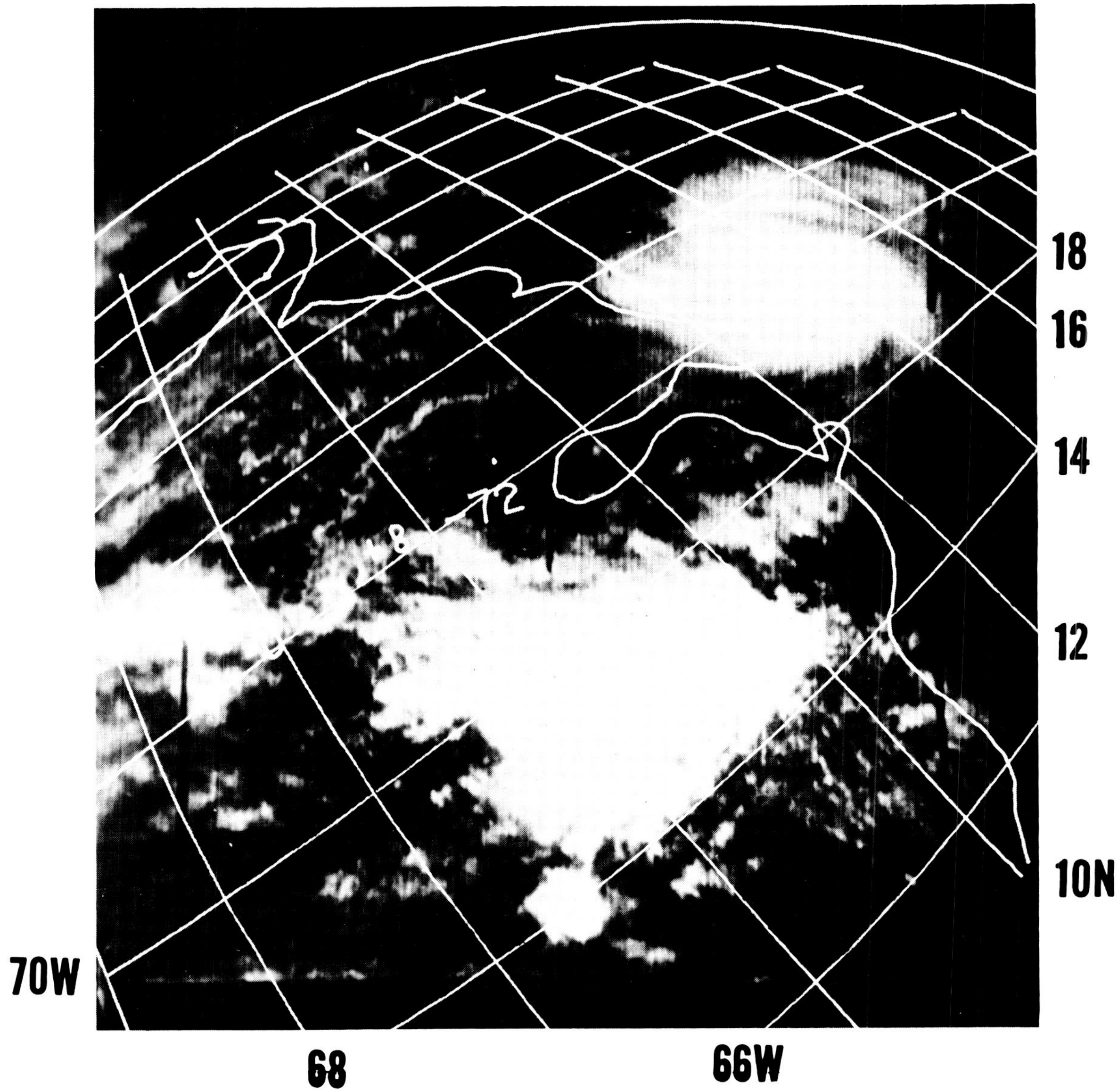


Figure 14

TIROS RADIATION DATA 8-12 MICRON FROM J DAY 009 AT 1545 Z FOR 012 MINUTES ORBIT 0133

Figure 15

TIROS RADIATION DATA WITH WORLD MAP OVERLAY

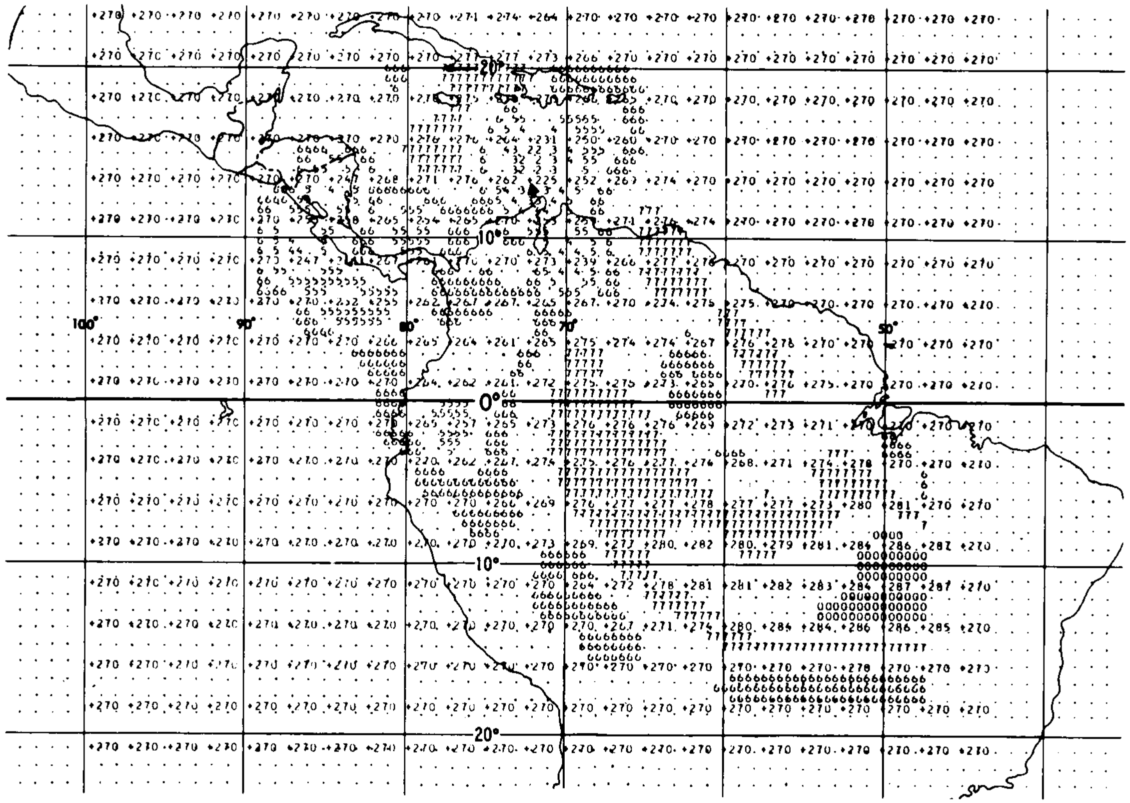
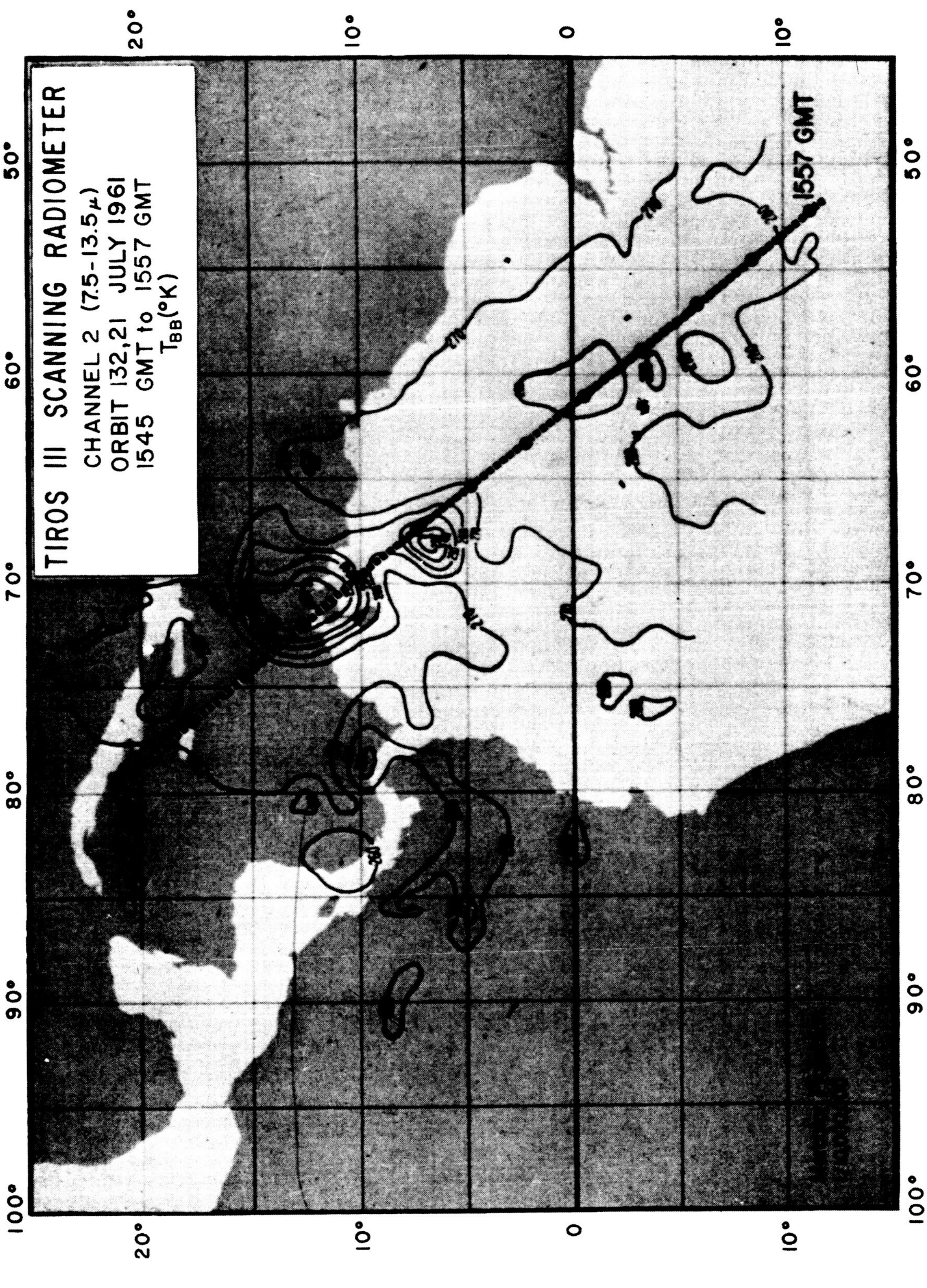
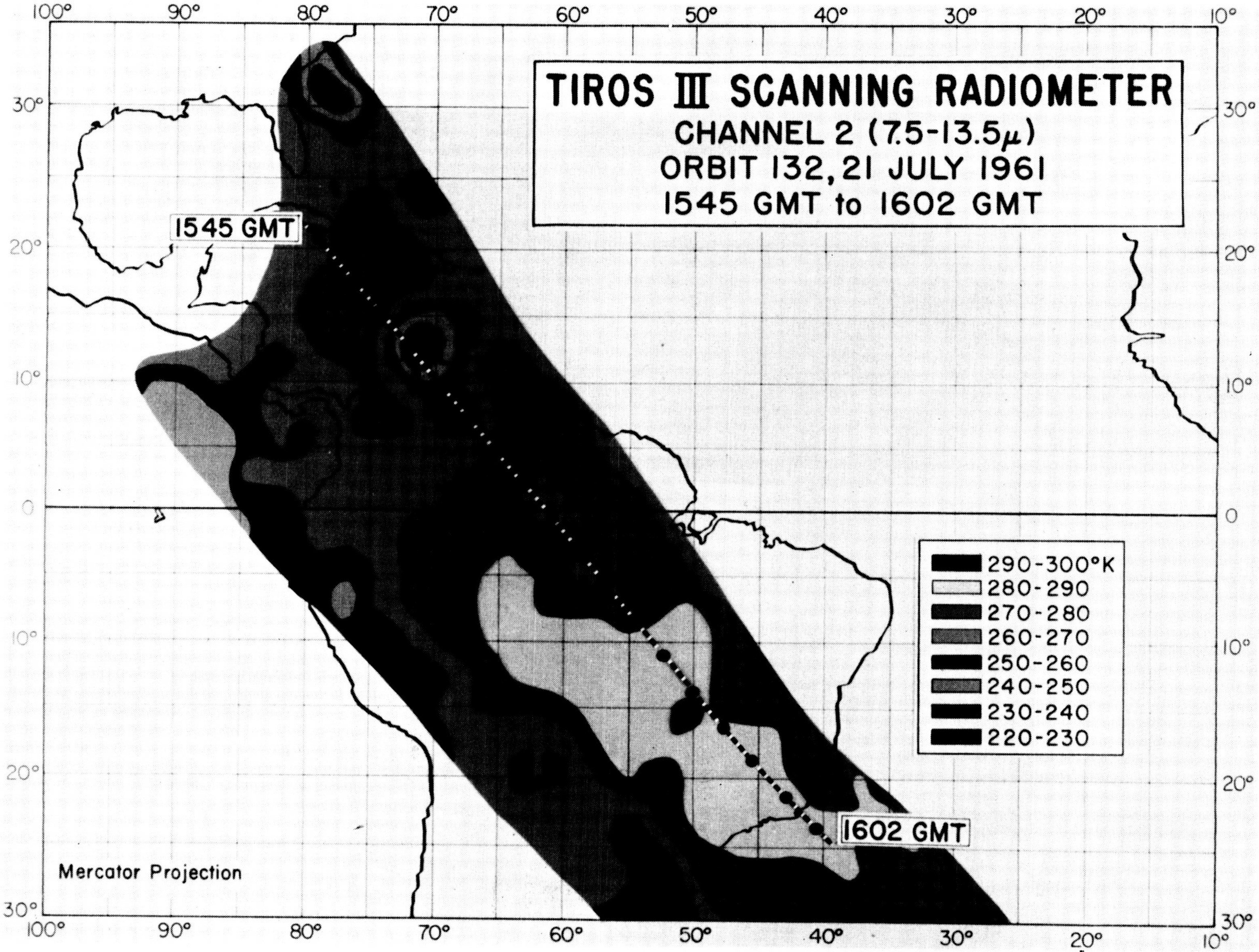


Figure 16



TIROS III SCANNING RADIOMETER
CHANNEL 2 (7.5-13.5μ)
ORBIT 132, 21 JULY 1961
1545 GMT to 1557 GMT
TBB(°K)
1557 GMT
20°
10°
0
10°
50°
60°
70°
80°
90°
100°

Figure 17



TIROS III SCANNING RADIOMETER
CHANNEL 2 (7.5-13.5μ)
ORBIT 132, 21 JULY 1961
1545 GMT to 1602 GMT
1545 GMT
1602 GMT
290-300°K
280-290
270-280
260-270
250-260
240-250
230-240
220-230
Mercator Projection
100°
90°
80°
70°
60°
50°
40°
30°
20°
10°
30°
20°
10°
0
10°
20°
30°

Figure 18

COMPOSITE MAP OF 'WINDOW' RADIATION (CHANNEL 2) AND SURFACE SYNOPTIC ANALYSIS COMBINED FROM DIFFERENT SOURCES

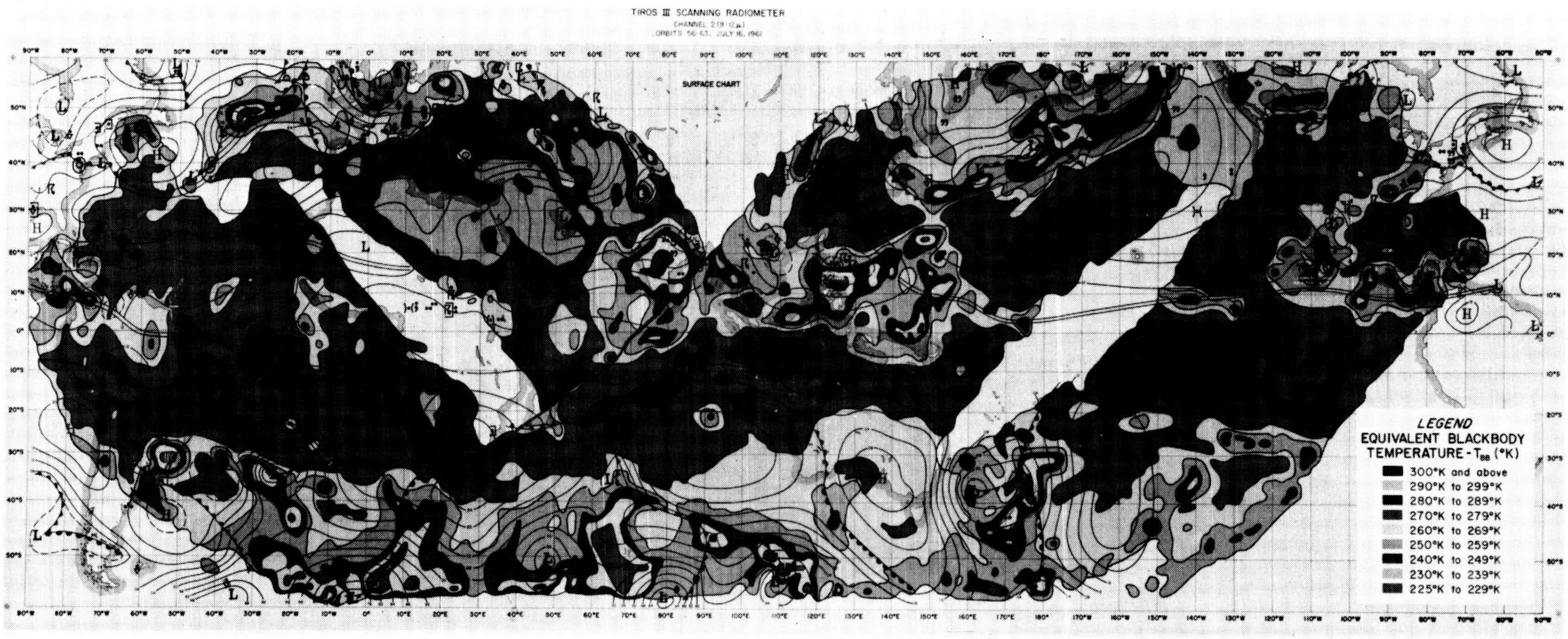


Figure 19

ENERGY FLUX FROM TIROS VII JUNE 1963 - AUGUST 1963

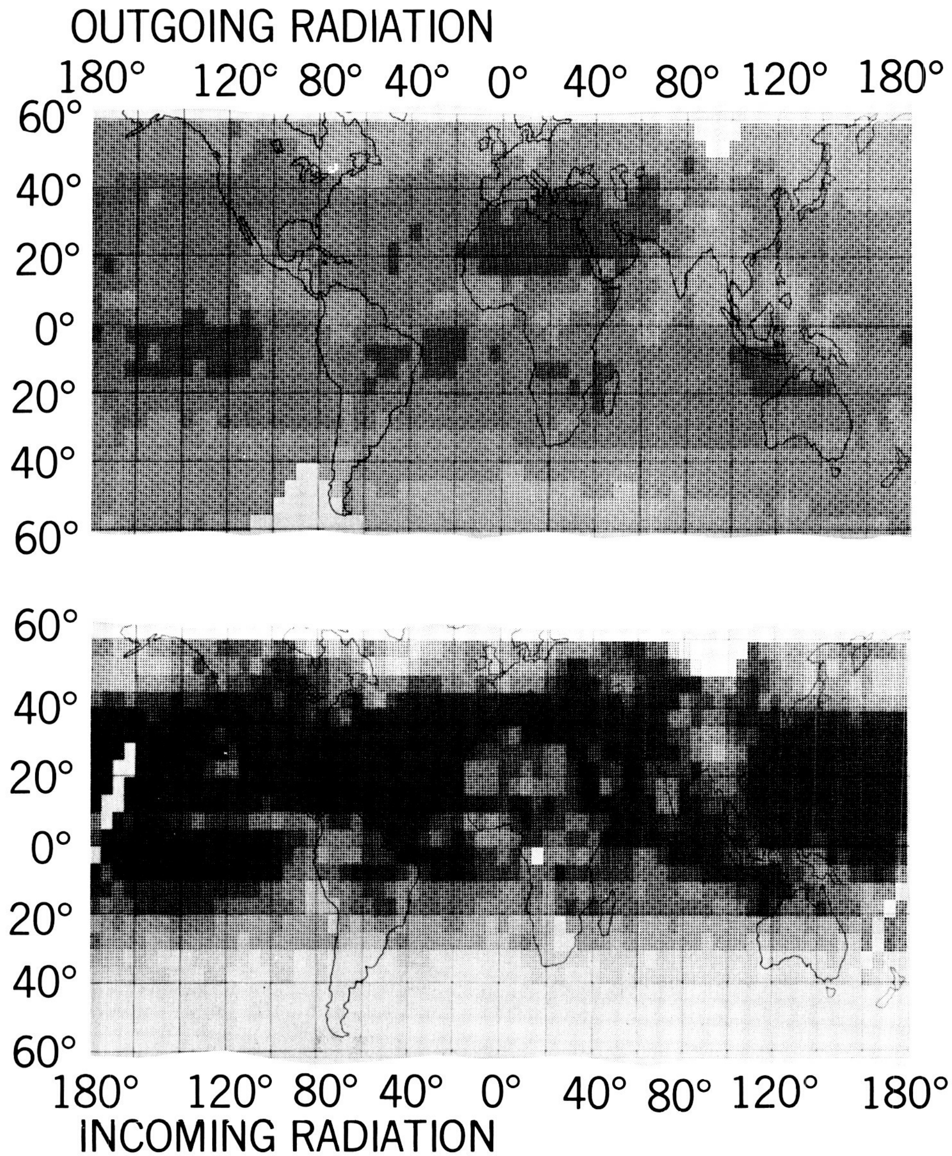


Figure 20

ENERGY FLUX FROM TIROS VII DECEMBER 1963 - FEBRUARY 1964

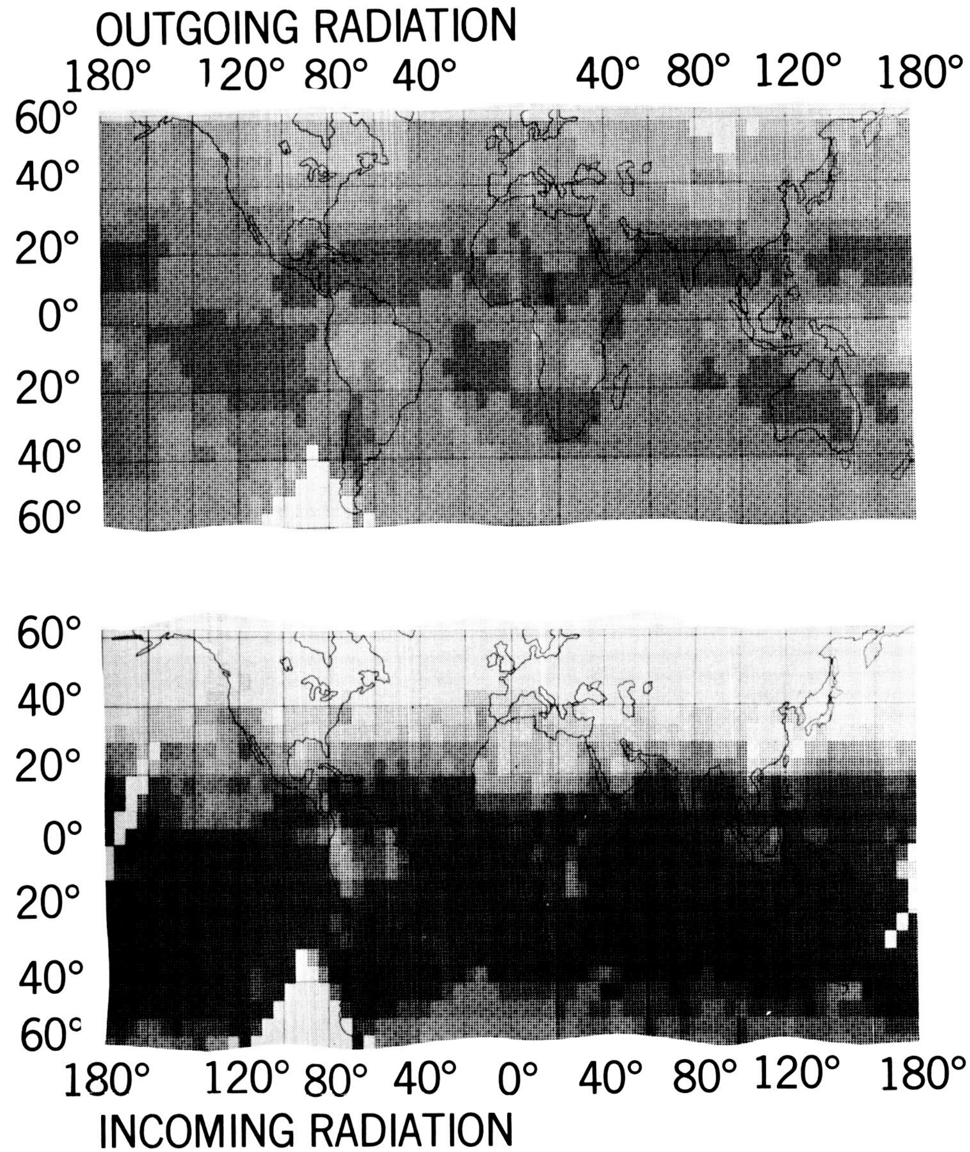


Figure 21

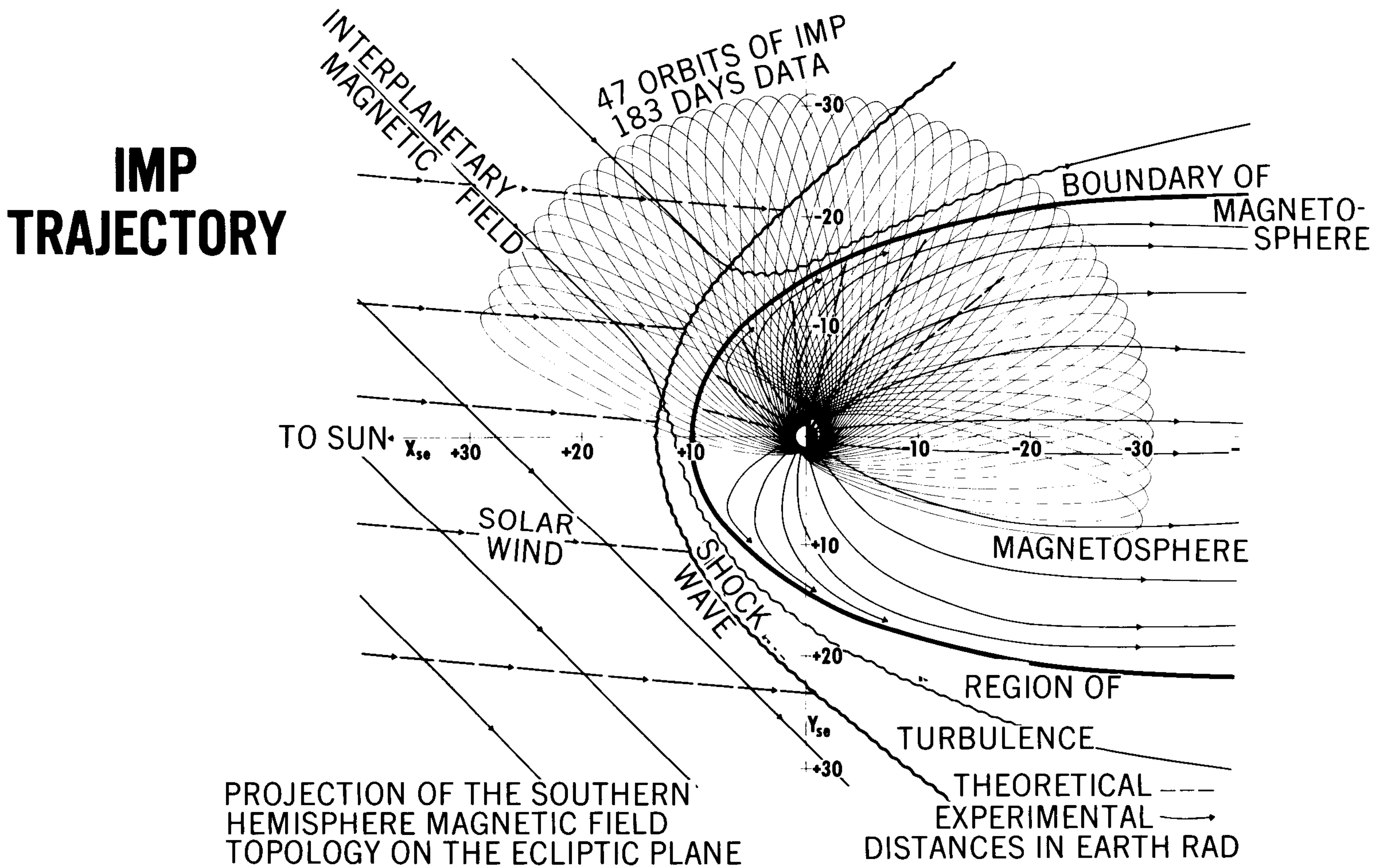


Figure 22. IMP Trajectory in Relation to the Earth and the Magnetosphere, 11/27/63 to 5/31/64

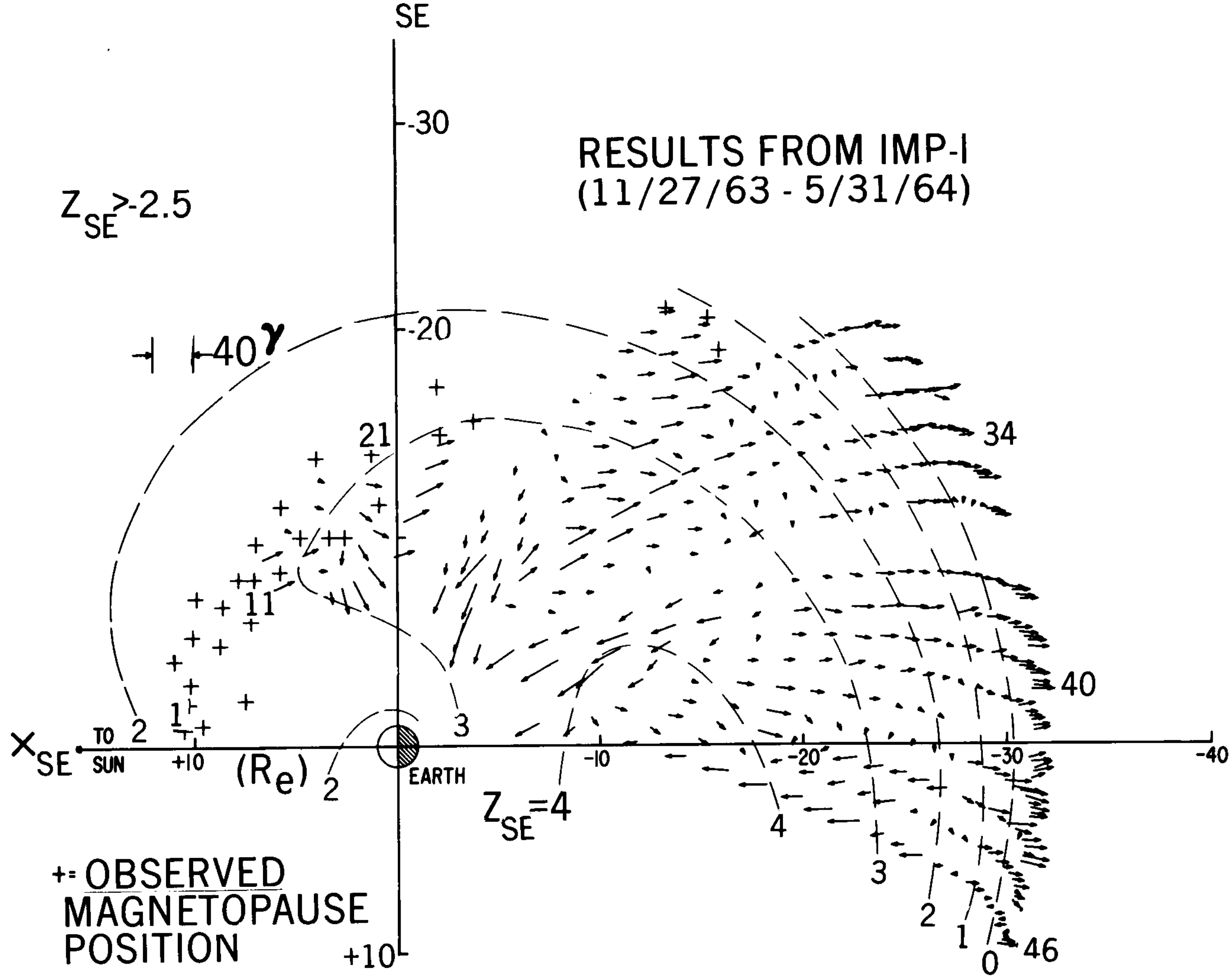


Figure 23. X_{SE} - Y_{SE} Component of Magnetosphere Field

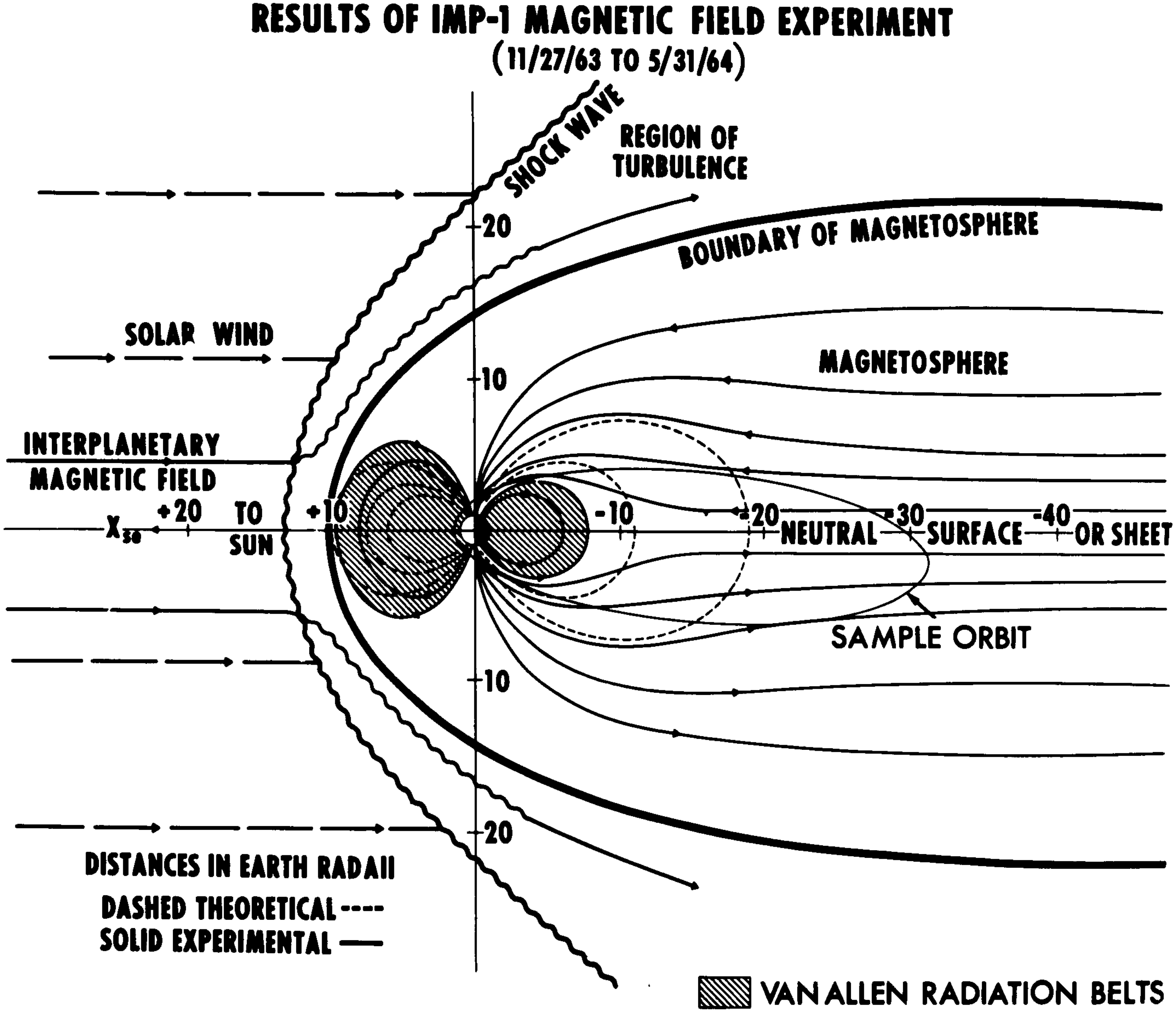


Figure 24. Projection of Magnetic Field Topology on Noon Midnight Meridian Plane

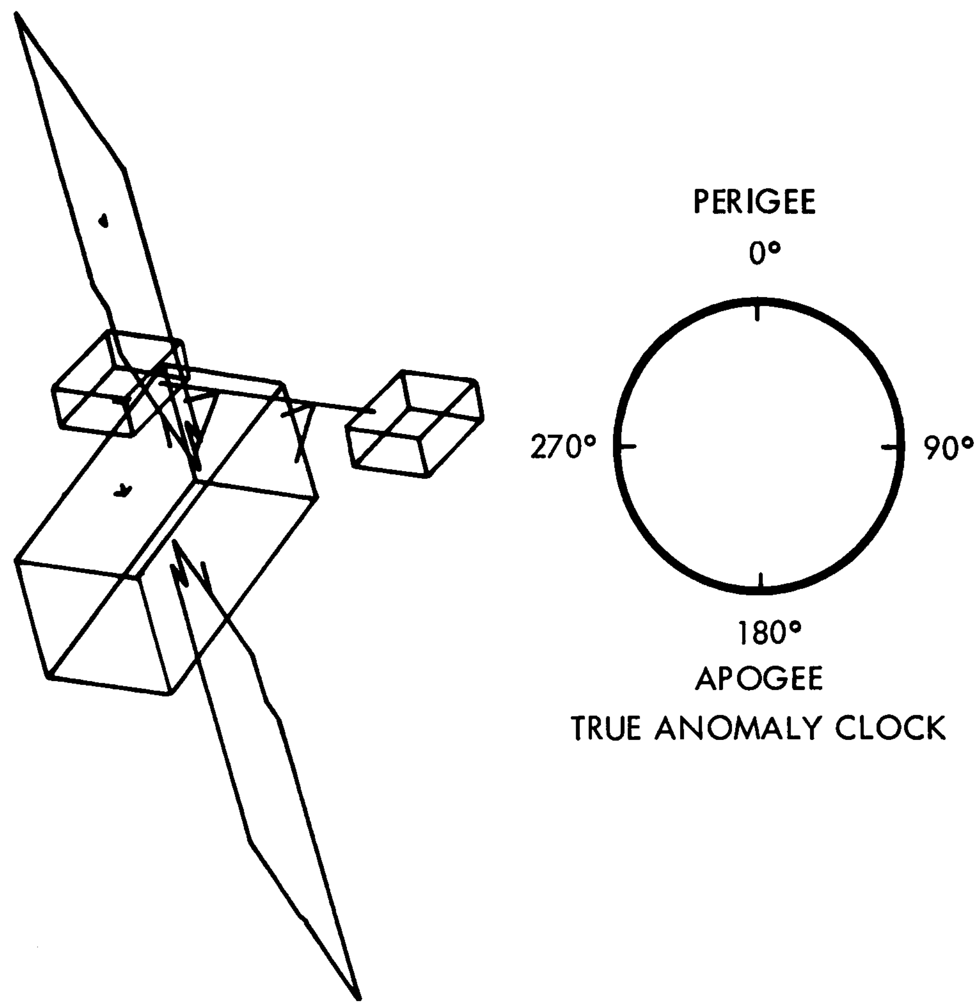


Figure 25. Sample Frame from Spacecraft Oriented Film (OGO)

TRACING THE PATHS OF TWO PARTICLES IN A BARRED SPIRAL GALAXY

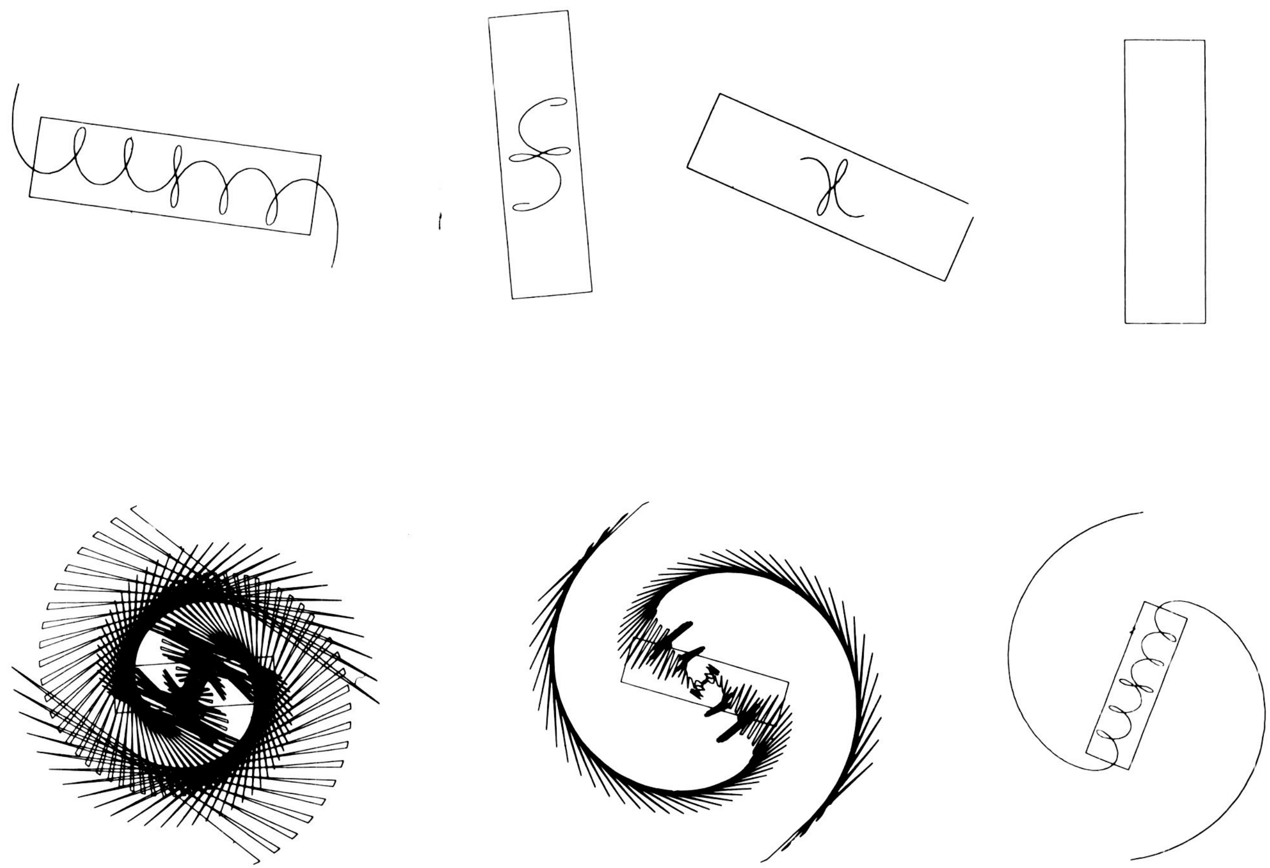


Figure 26. Tracing the Paths of Two Particles in a Barred Spiral Galaxy

TOPSIDE SOUNDER IONOGRAM

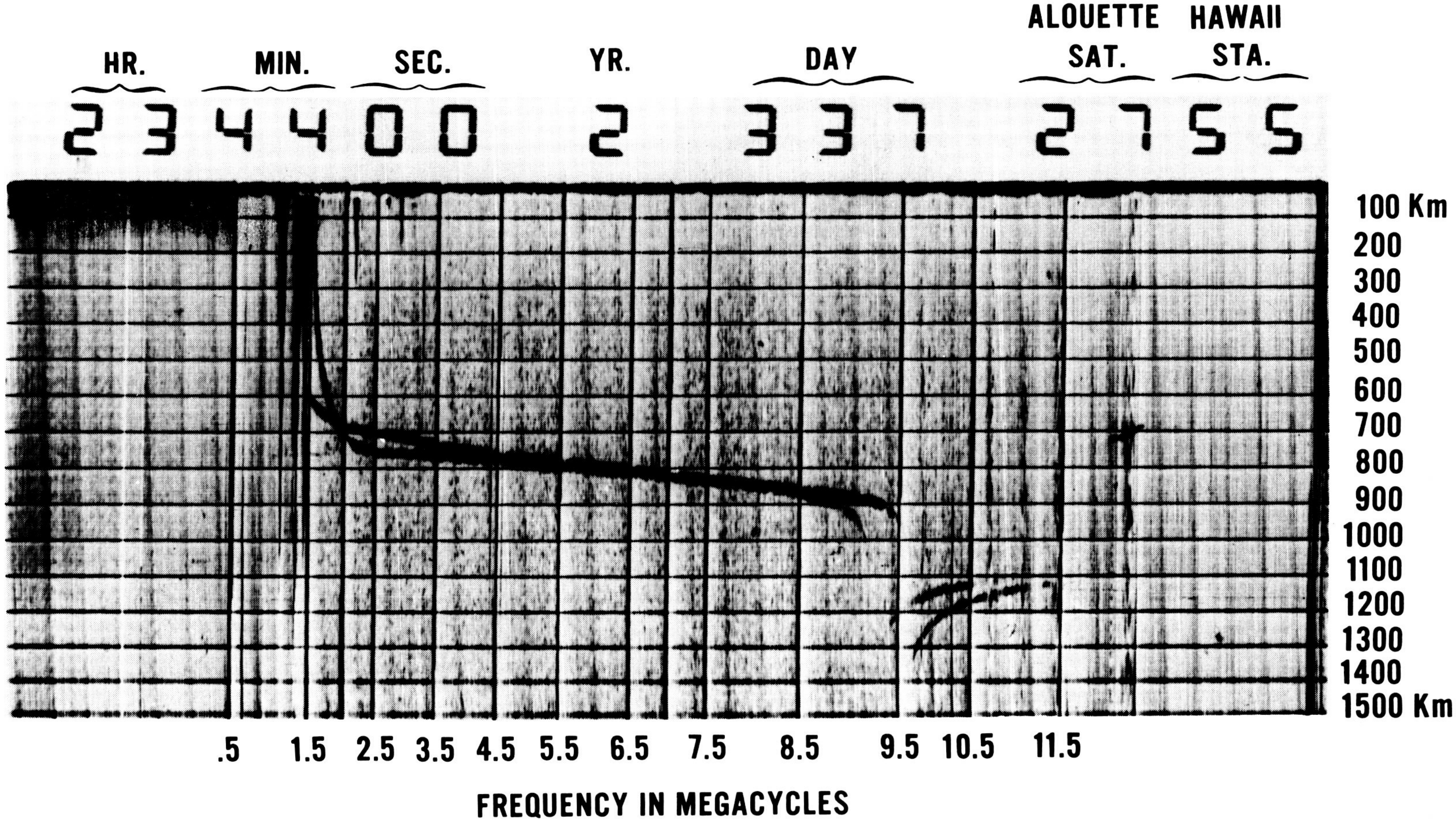


Figure 27

IONOGRAM DIGITIZER

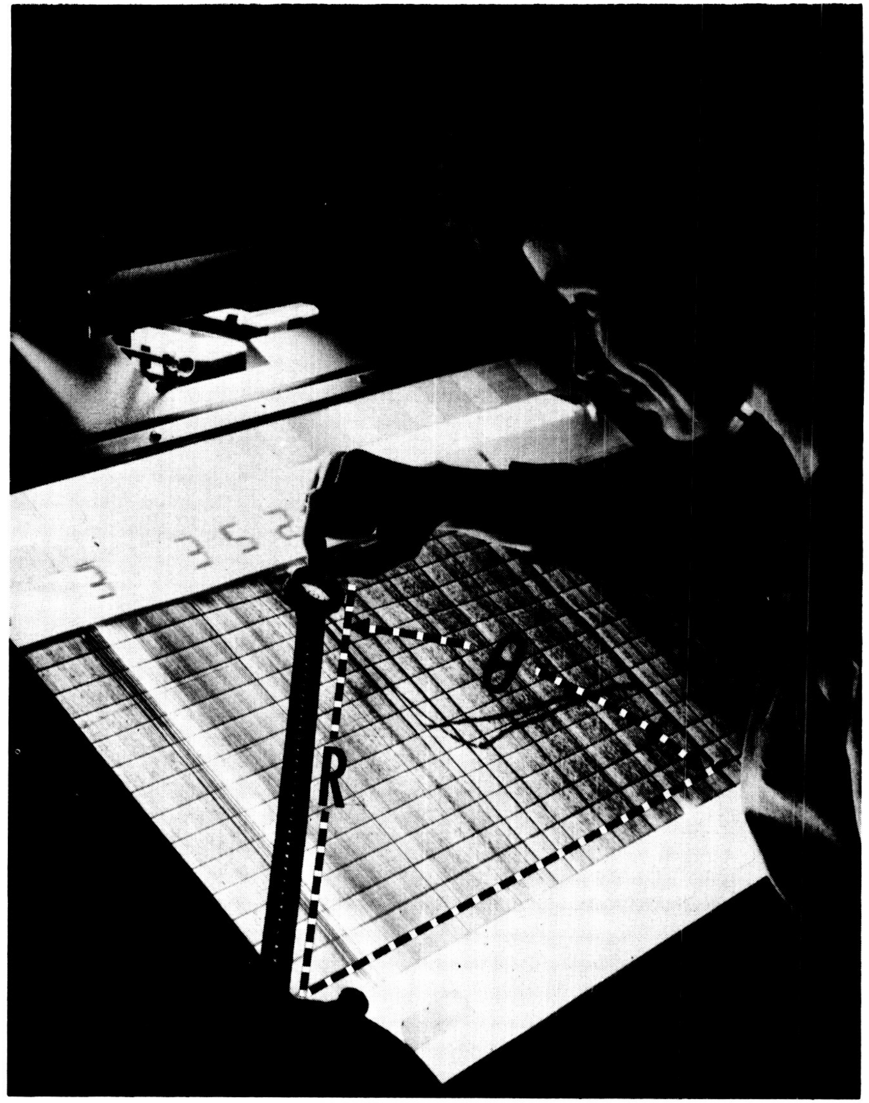


Figure 28